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Ion beam analysis of Fe-based Heusler alloys/Ge hetero-epitaxial interfaces toward spin transistors

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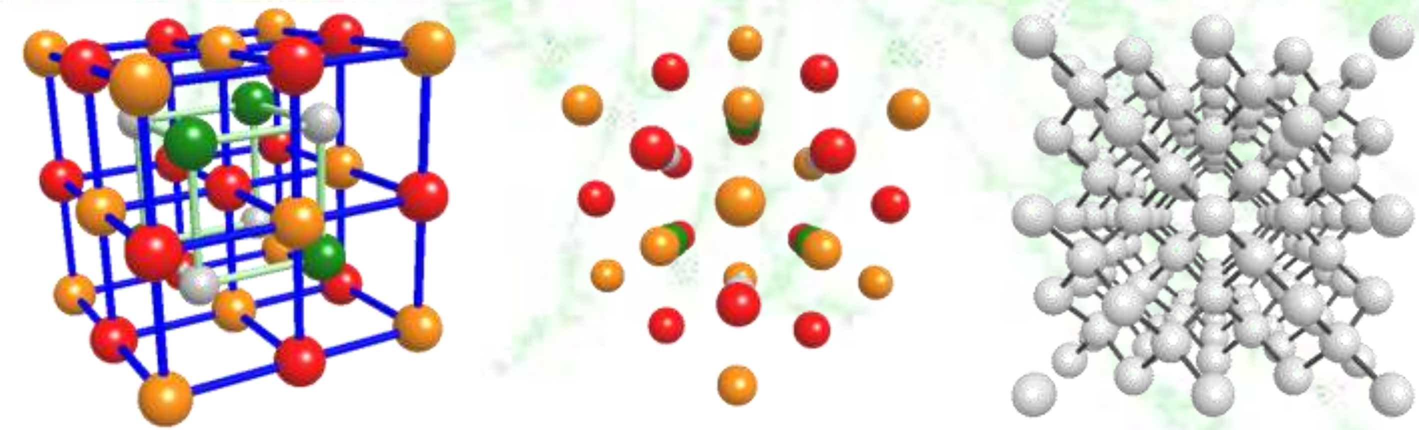
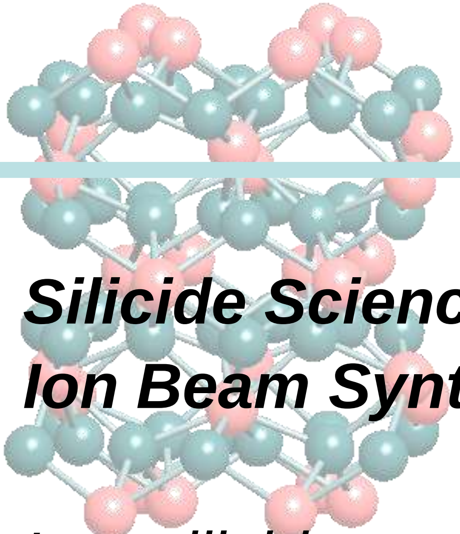


ver 3.0

Our Research

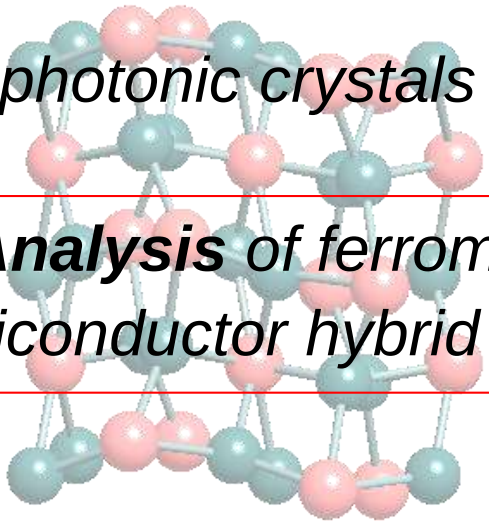


Silicide Science and Technology

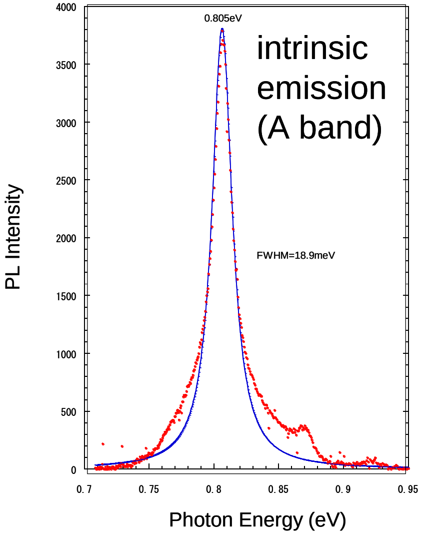
Ion Beam Synthesis *of iron silicides*

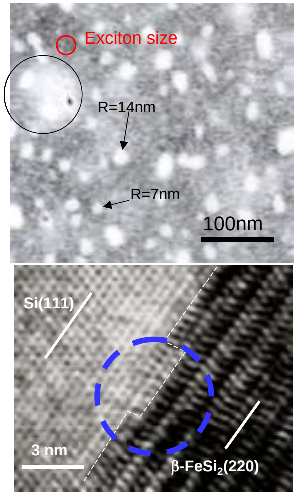
Iron silicide nanostructures for light emitter

Iron silicide photonic crystals



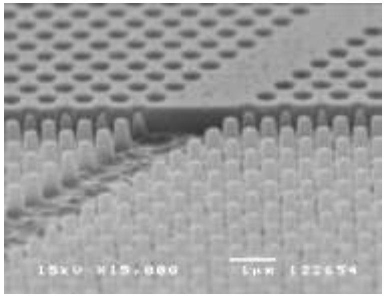
Ion Beam Analysis *of ferromagnetic silicide/semiconductor hybrid structure*





Photonic crystals

β-FeSi$_2$, Fe$_3$Si



Collaborator

Prof. M. Miyao, Prof. K. Hamaya, Prof. T. Sadoh
Kyushu University,
on MBE of ferromagnetic alloy films on semiconductors

Dr. M. Narumi, Dr. S. Sakai, Dr. K. Takahashi
Japan Atomic Energy Agency (JAEA)
on Ion beam analysis and development of beam lines
toward low temperature ion channeling experiments

Students graduated from Maeda Laboratory,
at Kyoto University, on RBS measurements.

Prof. Y. Terai, Dr. Y. Ando, Osaka University
on characterization of films

Outline

1. Motivation

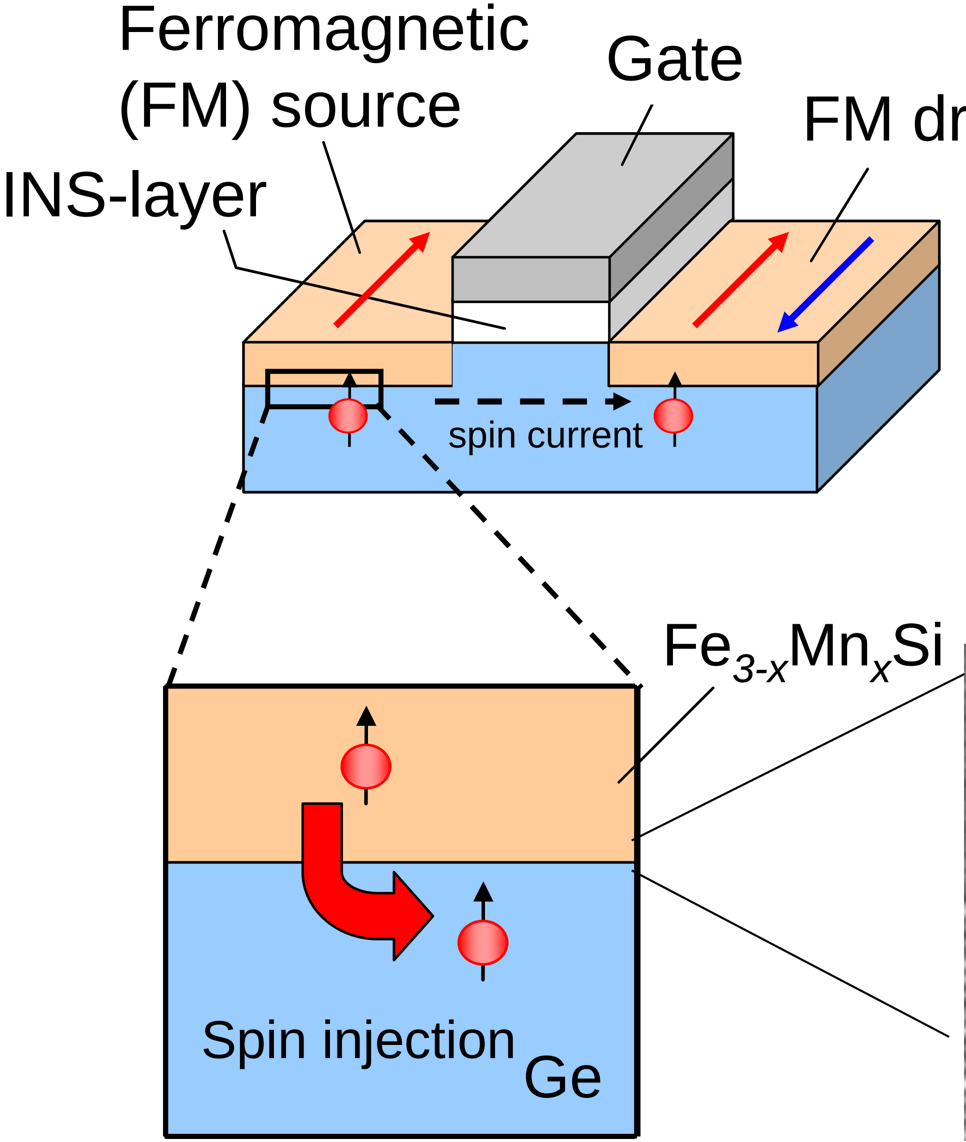
   Ion Beam Analysis of materials for Spintronics.

2. Ion Channeling and its application to quantitative evaluation of disordering of some Heusler alloy films epitaxially grown on Ge(111).

3. Topic : Spin injection behavior related to quality of epitaxial growth of ferromagnetic (FM) Heusler alloy films Fe_3Si on Si(111).

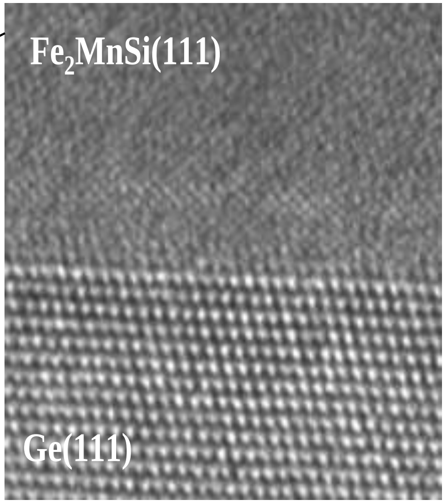
4. Conclusions

One of Goals of Spintronics, ***Spin FET***



Spin-FET has a same device structure as MOSFET.
We expect it on
very high frequency operation and very low consuming power.

FM source epitaxially grown on Ge(111)



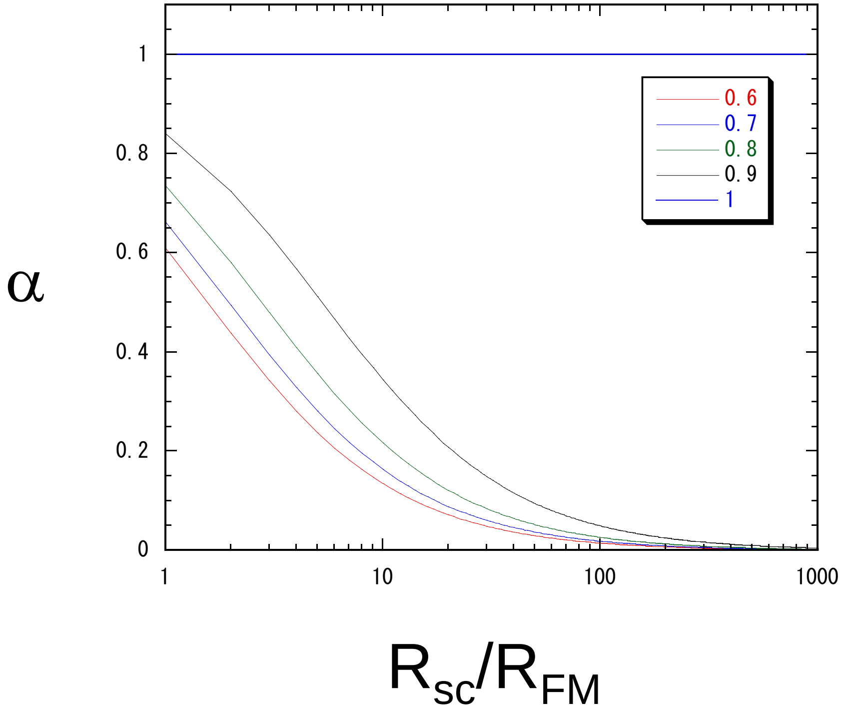
High quality heteroepitaxial interface realized by low temperature MBE technique.

K. Ueda et al: Appl. Phys. Lett. 93, (2008) 112108-1-3.

Efficiency of Spin Injection from FM into SC

$$\alpha = P_{\mathrm{SC}} / P_{\mathrm{FM}}$$

$$= \frac{1}{1 + \left(1 - P_{\mathrm{FM}}{}^{2}\right)\left(R_{\mathrm{SC}} \big/ R_{\mathrm{FM}}\right)}$$



P_{FM} : Spin polarity of FM

R_{sc} : Electrical resistivity of SC

R_{F} : Electrical resistivity of FM

In usual case, R_{sc}>>$R_{F,}$ *so that* **α<<1**

that is, Resistivity gap problem,

we have to overcome it for Spintronics.

Possible solutions

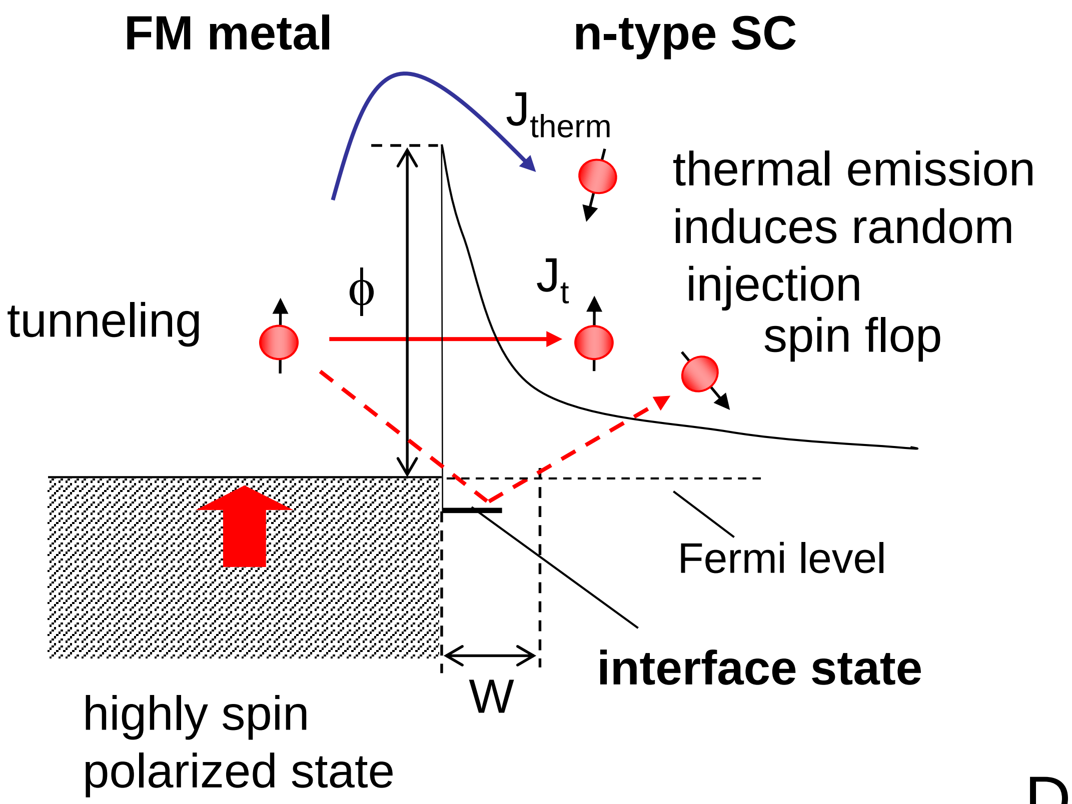
- Using *half metallic FM material* as an electrodes such as Fe_2MnSi etc.

  (if possible, the problem remains.)
- Using Magnetic SC with highly polarized spin states. (in future, possible?)

- Using spin injection by electron tunneling through a Schottoky barrier. (Actually promising)

K. Takanashi, JJAP (2011)

Spin injection by electron tunneling though Schottky barrier



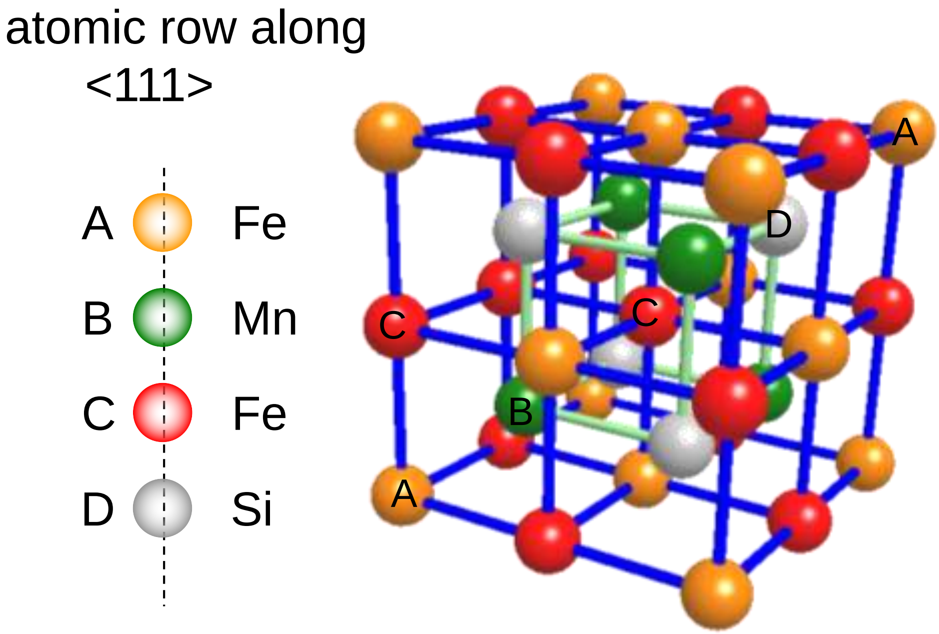
Scheme of spin injection by electron tunneling through a Schottoky barrier

Conditions for Spin injection

We need thinner barrier width enough to cause electron tunneling and higher barrier hight enough to prevent thermal emission.

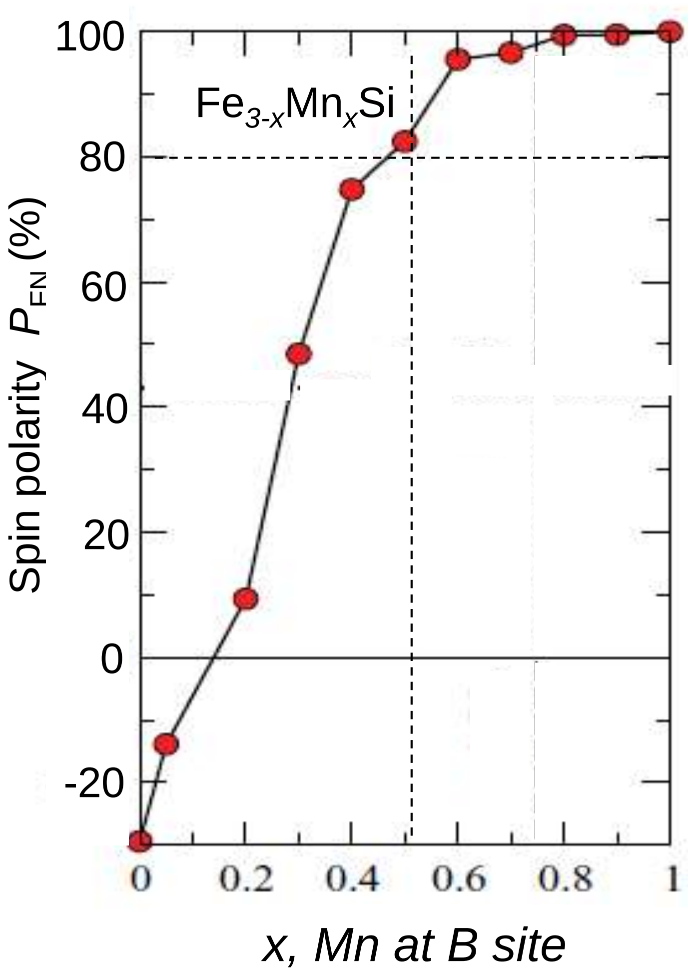
Delta dope technology and Reduction of interface states by high quality MBE

$Fe_{3-x}Mn_xSi$ (FMS) : Spin polarization



L2$_1$ type Heusler alloy
with ordered lattice Fe_2MnSi

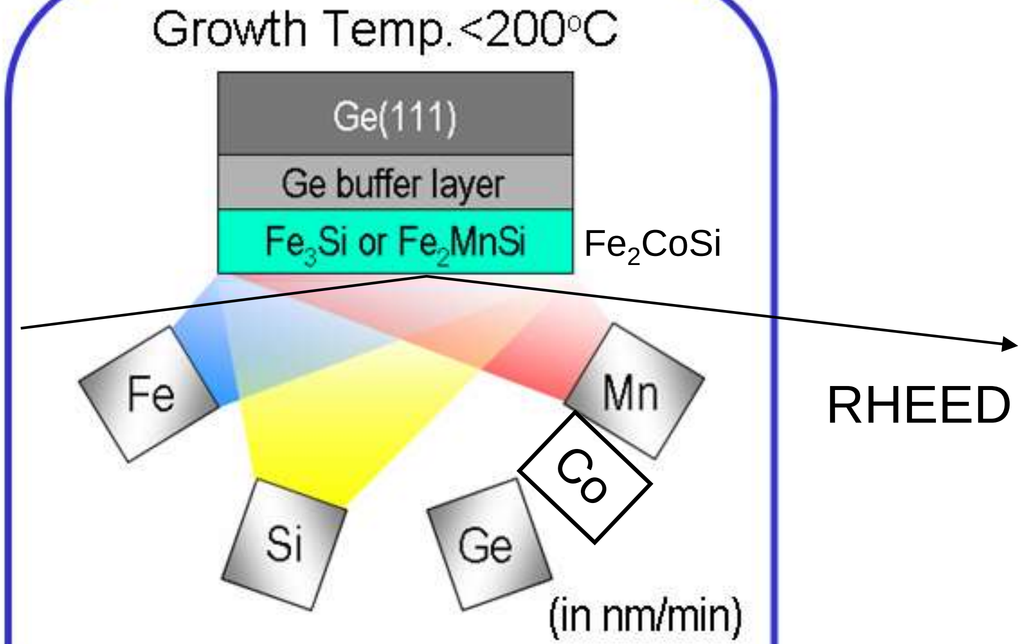
Stoichiometric Fe_2MnSi is estimated to be half metallic. Mn occupation at the B site affects spin polarization as shown in right figure.



M. Lezaic et al.: Phys. Rev. B ***83*** *(2011) 094434.*

Low temperature MBE realized High quality Epitaxy

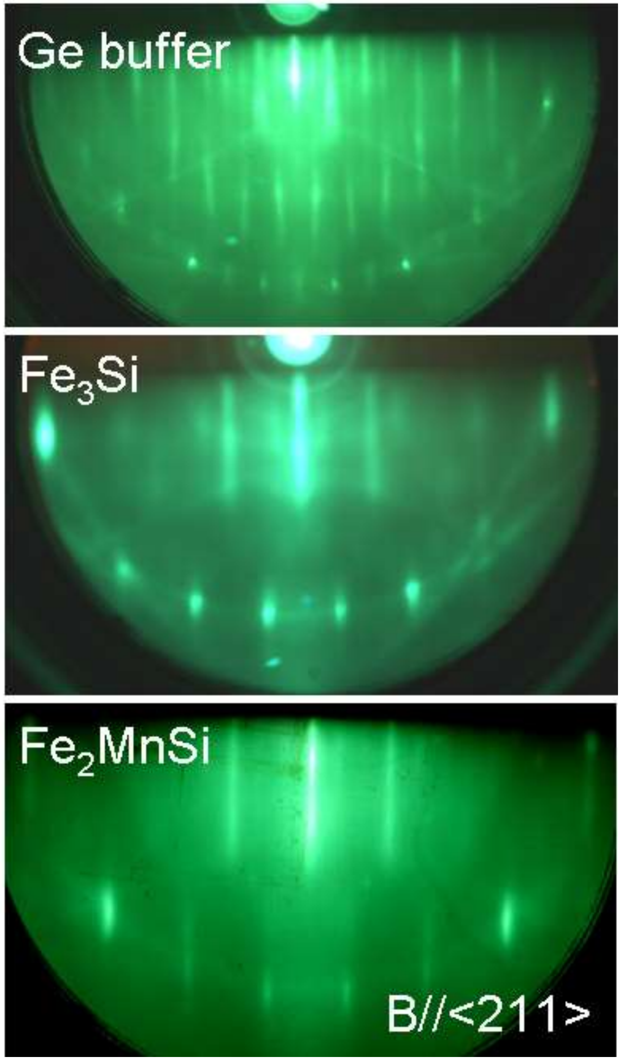
Low Temperature MBE



	Fe	Si	Mn
Fe_3Si	0.12	0.04	
Fe_2MnSi	0.047	0.04	0.015

Co-evaporation

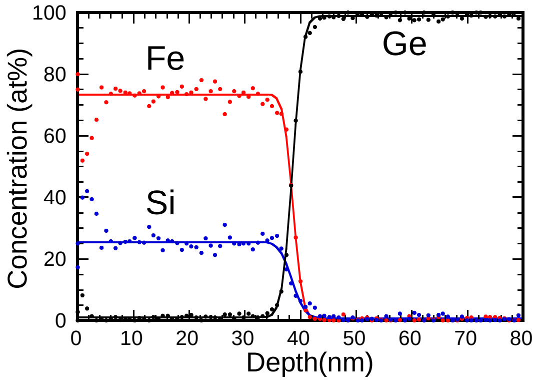
RHEED Patterns

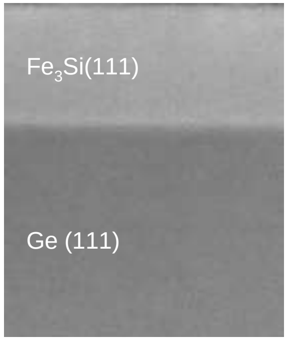


K. Ueda et al: Appl. Phys. Lett. 93, (2008) 112108-1-3.

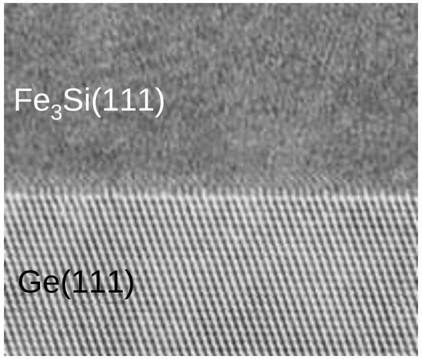
Growth temperature T_G is crucial for high quality epitaxy of FM F_3Si/Ge

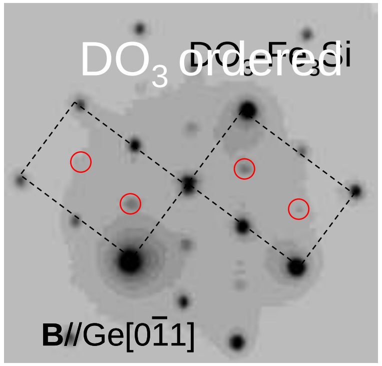
T_G=130°C



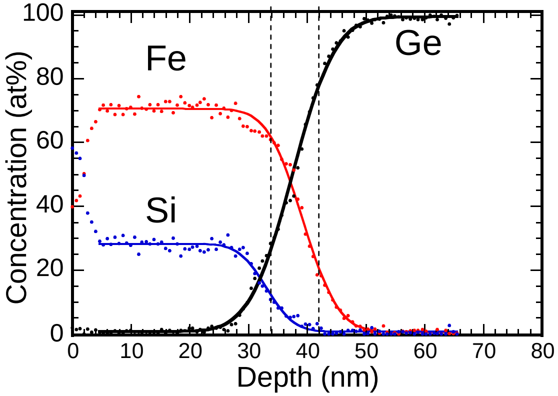


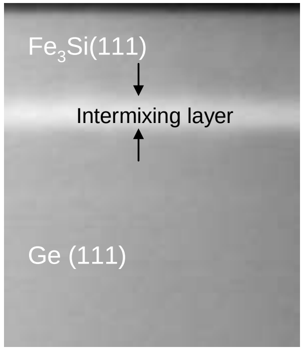
HAADF



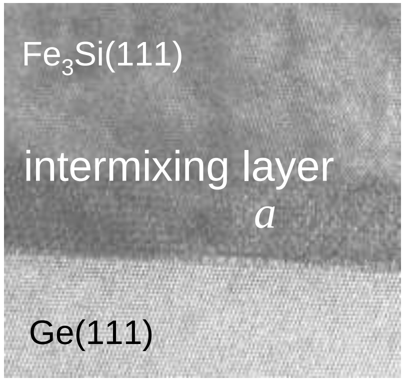


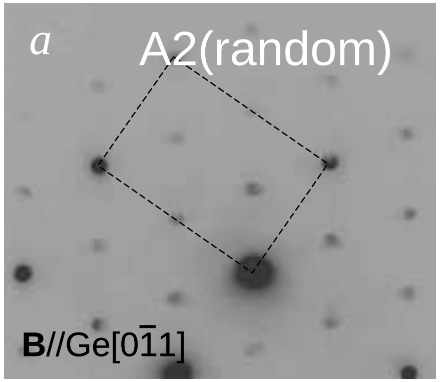
T_G=300°C





HAADF





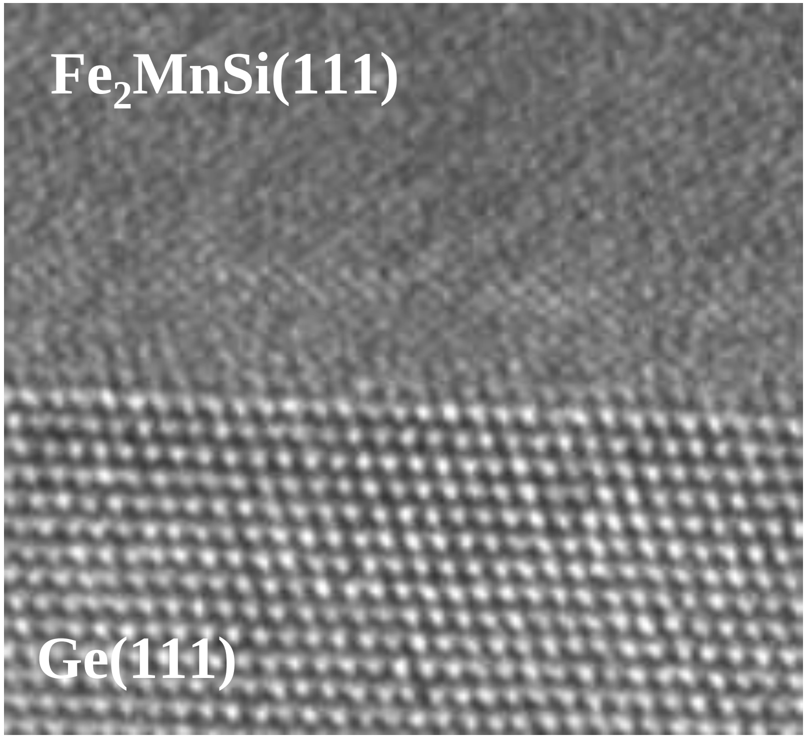
Low T_G is much better, we can prevent active interdiffusion between FM and Ge substrates and keep a DO_3 ordered lattice during growth.

Low temperature MBE technique

XTEM, SAD observations of $Fe_2MnSi(111)/Ge(111)$

XTEM image

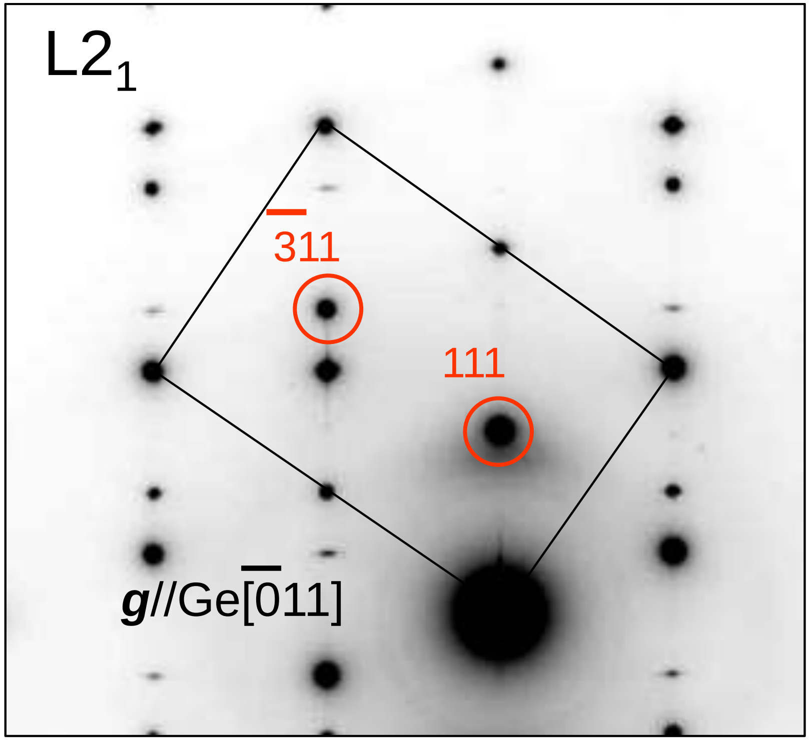
$Fe_2MnSi(111)//Ge(111)$



K. Ueda et al: Appl. Phys. Lett. 93, (2008) 112108-1-3.

SAD pattern

$Fe_2MnSi<111>//Ge<111>$



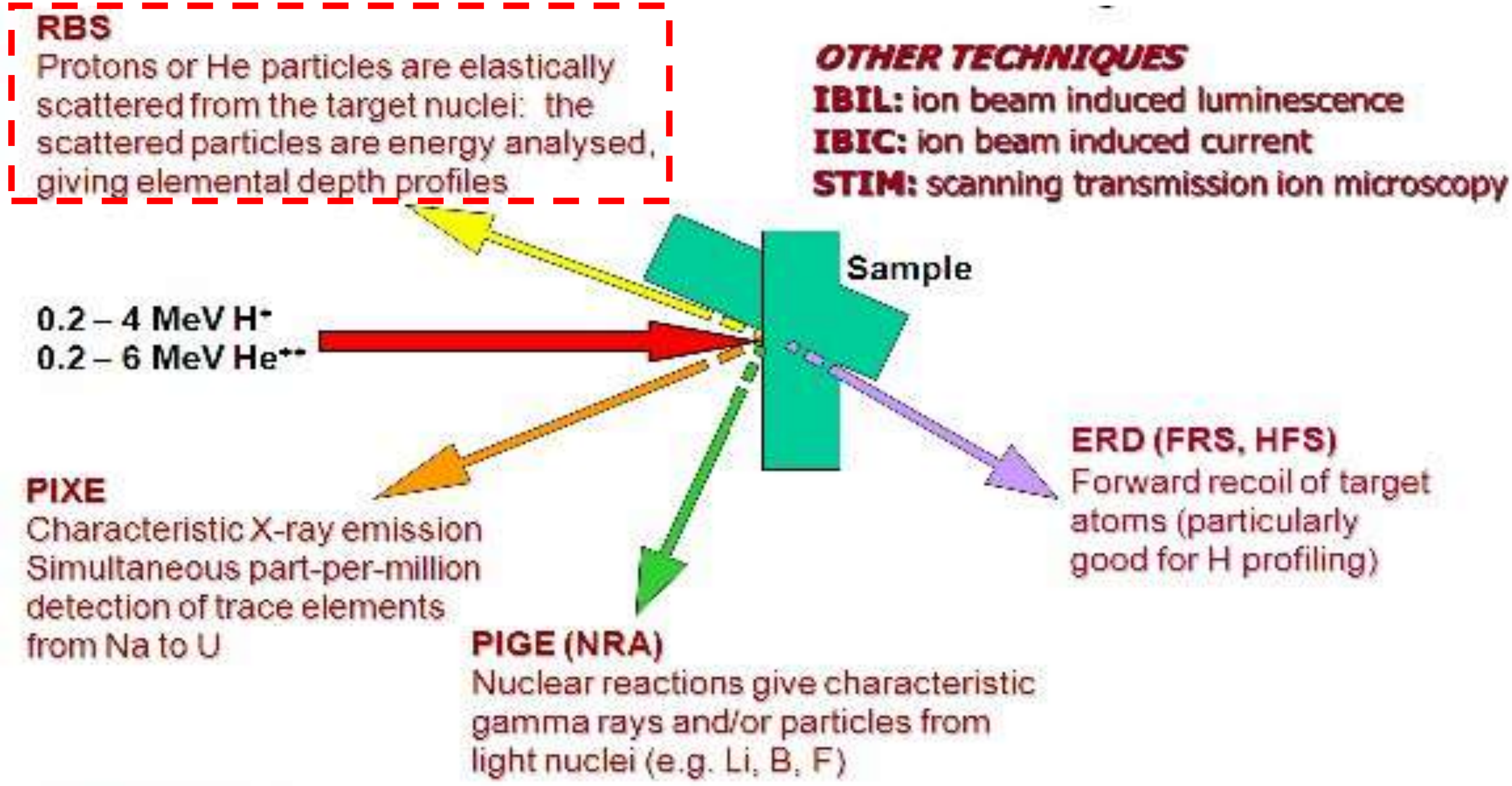
○ $L2_1$ super lattice reflection

XTEM brings direct information of epitaxial interfaces, however, dose not teach the in-plain information at spin injection interfaces to us.

2.

Introduction to Ion Channeling and its application to Quantitative analysis of disordering of some Heusler alloy films epitaxially grown on Ge(111).

Kinds of IBA



RBS
Protons or He particles are elastically scattered from the target nuclei: the scattered particles are energy analysed, giving elemental depth profiles

OTHER TECHNIQUES
IBIL: ion beam induced luminescence
IBIC: ion beam induced current
STIM: scanning transmission ion microscopy

Sample

0.2 – 4 MeV H^+
0.2 – 6 MeV He^{++}

ERD (FRS, HFS)
Forward recoil of target atoms (particularly good for H profiling)

PIXE
Characteristic X-ray emission
Simultaneous part-per-million detection of trace elements from Na to U

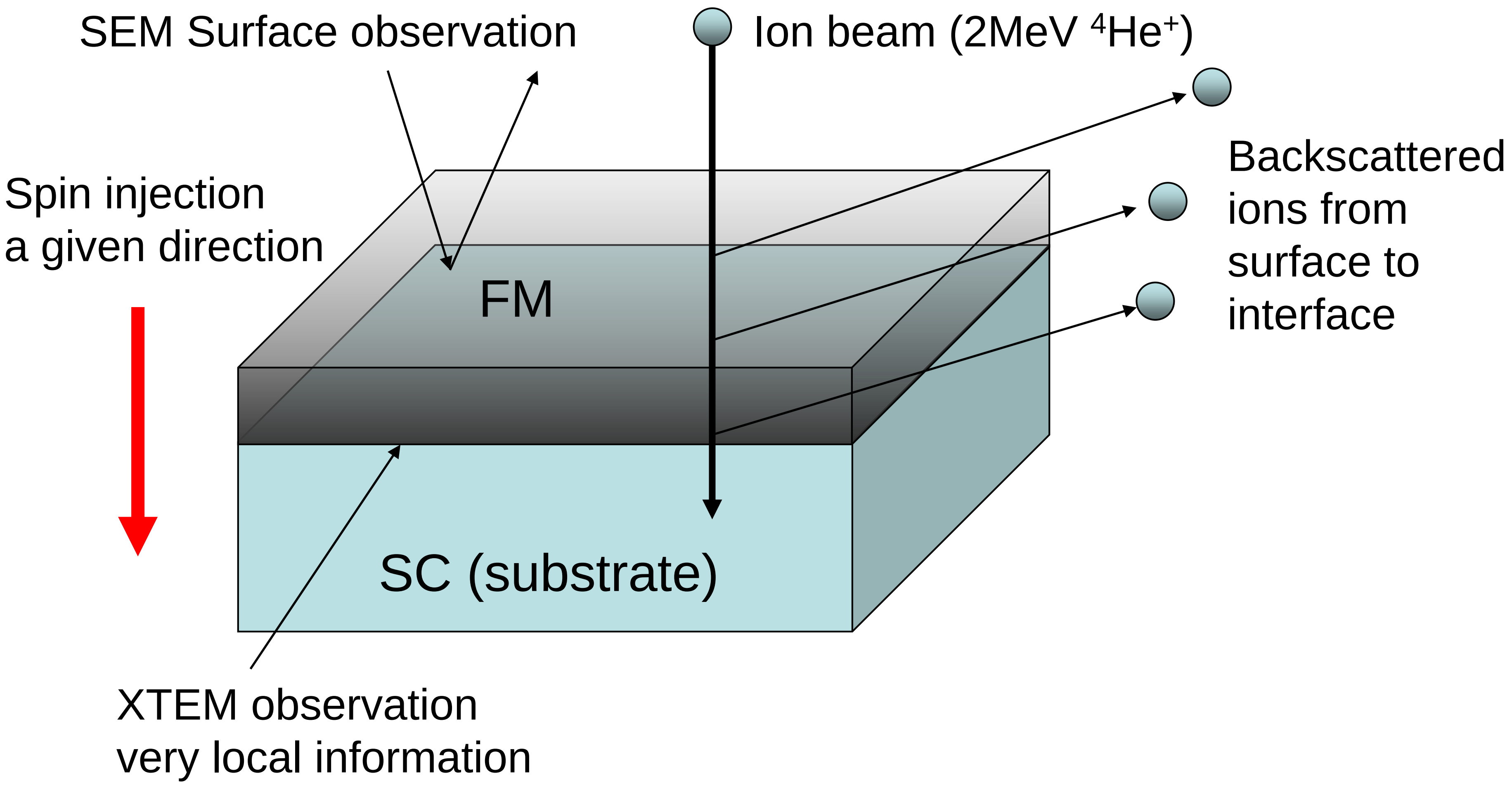
PIGE (NRA)
Nuclear reactions give characteristic gamma rays and/or particles from light nuclei (e.g. Li, B, F)

Ion Beam Analysis involves the use of an energetic ion beam to probe the surface of a material to reveal details of the elemental and structural details of it make up.

cited from SCRIBA, University of Surrey

Why do we need IBA?

IBA: Ion Beam Analysis


SEM Surface observation

Ion beam (2MeV $^4He^+$)

Backscattered ions from surface to interface

Spin injection a given direction

XTEM observation very local information

Using IBA, we can obtain not only atomic information at a tentative spin injection interface but also information from surface and the interface under nondestructive sample conditions.

Advantages of IBA

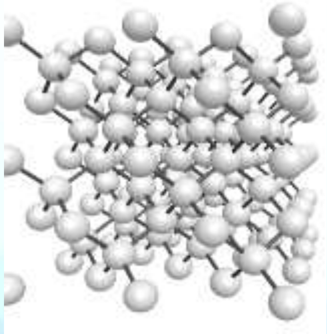
- Nondestructive

  under low dose of incident ions
- element resolution analysis
- Depth analysis
- Average information at analyzing macro-area
- Usage of channeling techniques for

  analysis of depth distribution of disorder, location of impurity

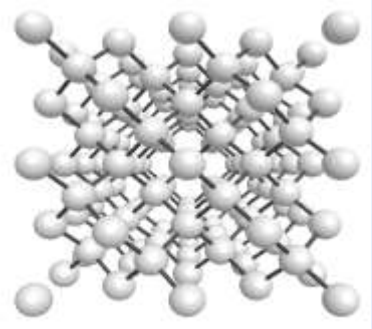
Rutherford Backscattering

- Random scattering gives information of depth distribution of elements involved in a sample.



Projection of atomic raw tilted by 5 degrees seems a random atomic arrangement.

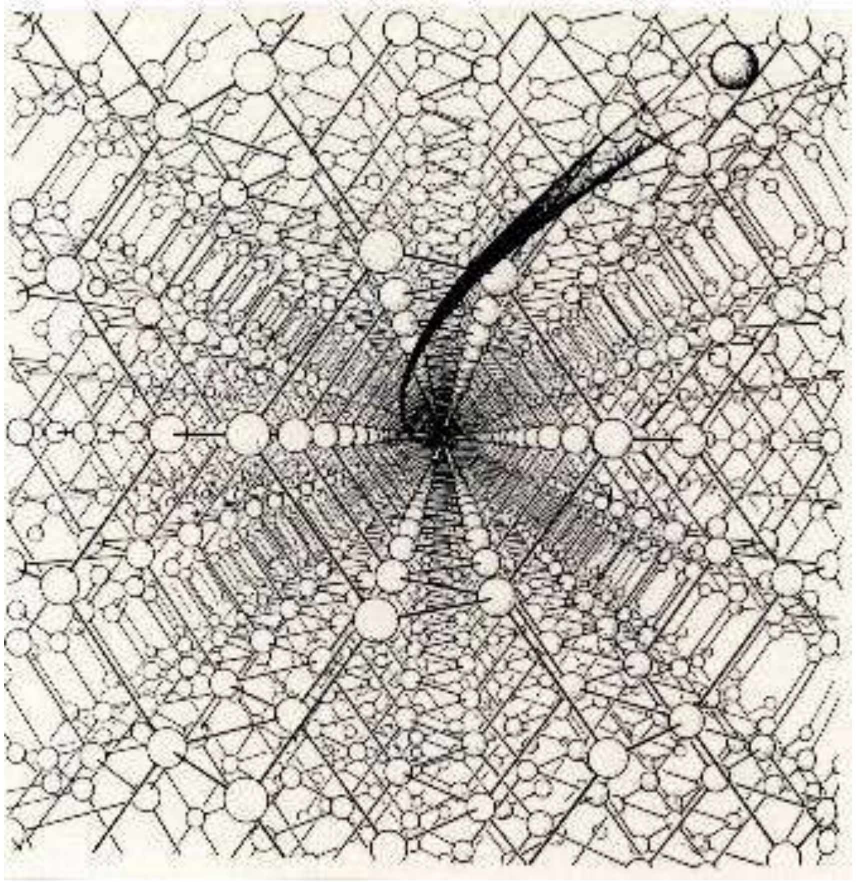
- ***Channeling*** gives information of amount and depth distribution of disorder, location of impurity in the lattice site, and composition and thickness of disordered surface layer.



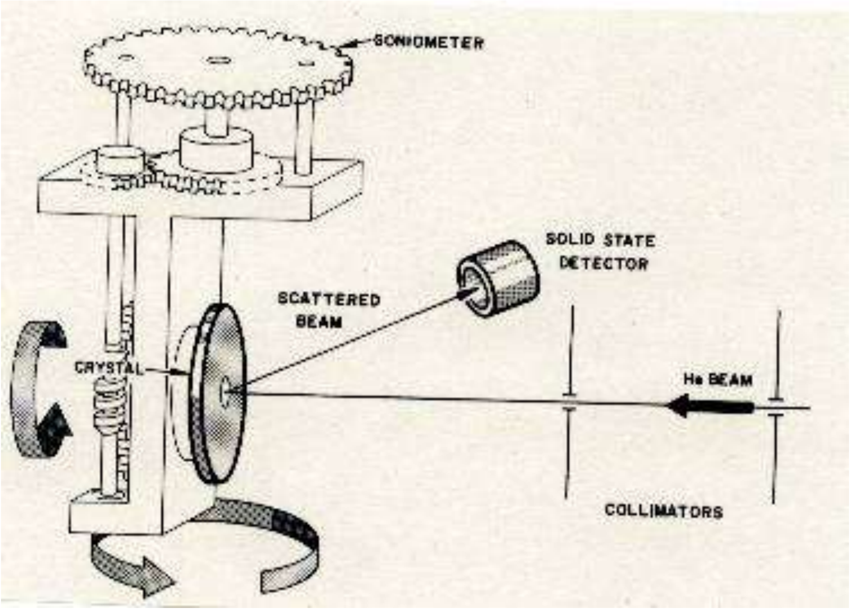
⊗ Ge<111> raw

Wei-Kan Chu et al., Backscattering Spectrometry, AP

Ion Channeling in crystal



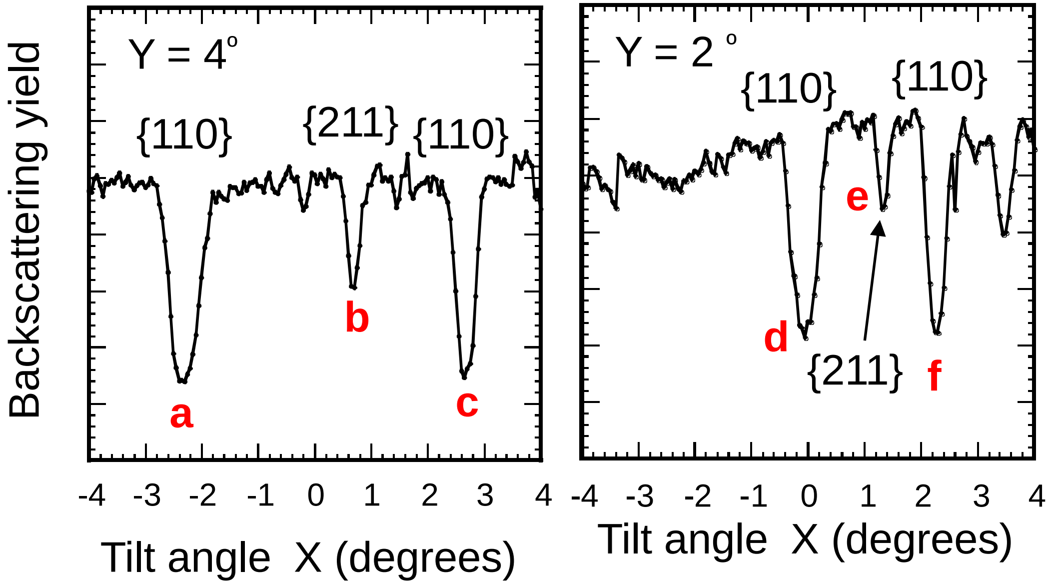
"Channeling in crystals"

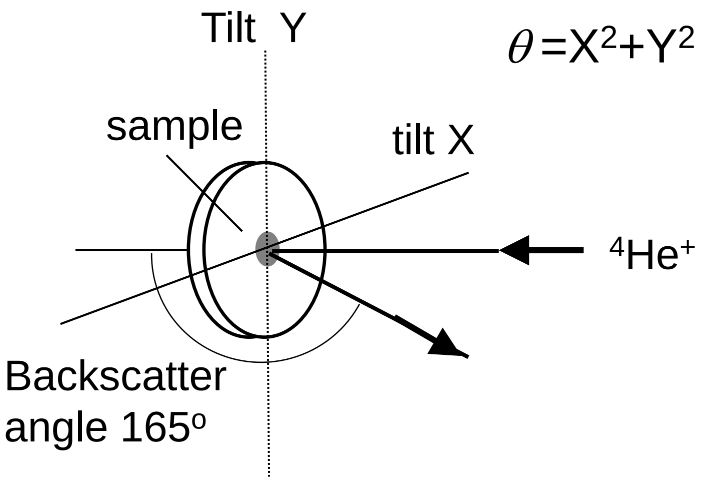


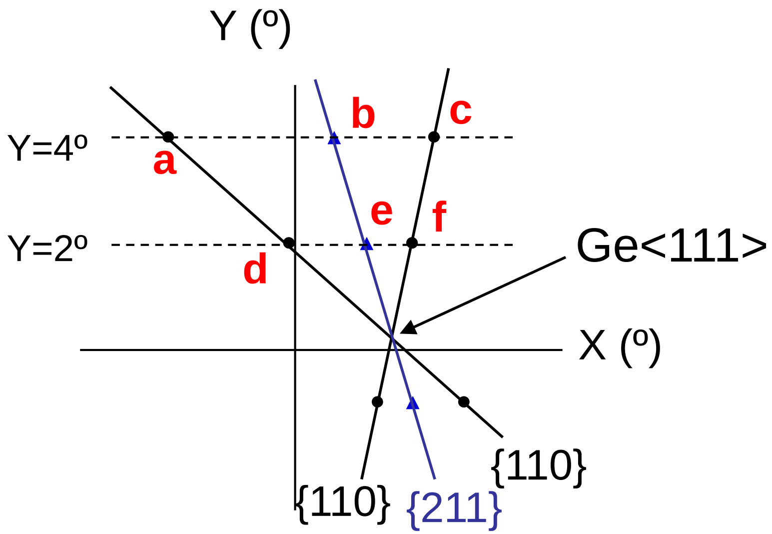
L.C. Feldman, J. W. Mayer, S. T. Picraux, "Materials analysis by ion channeling", Academic Press, 1982.

incident Ions from a specific direction into crystals can travel inside of the crystal channel, so that backscattering yield and stopping power decreases drastically.

Alignment of crystal axis, Case of Ge<111>





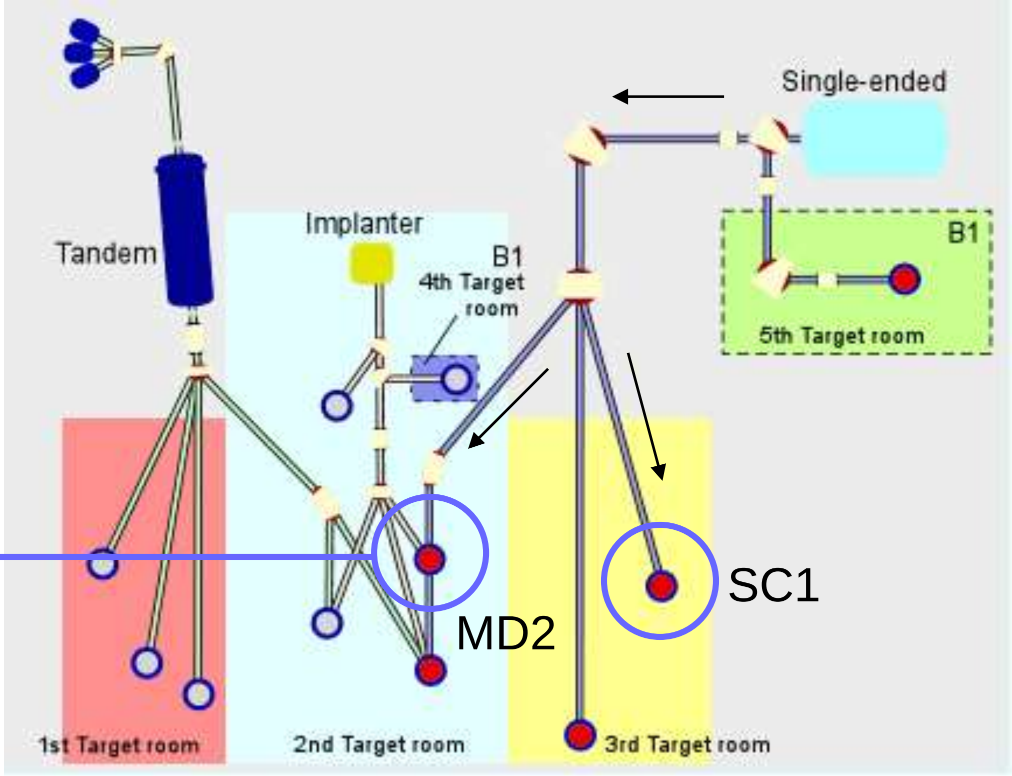


On Ge(111) plain, the zone axis of Ge<111> can be found by tilting along two specific direction, X and Y.

This alignment of the axis controls accuracy of ion beam channeling.

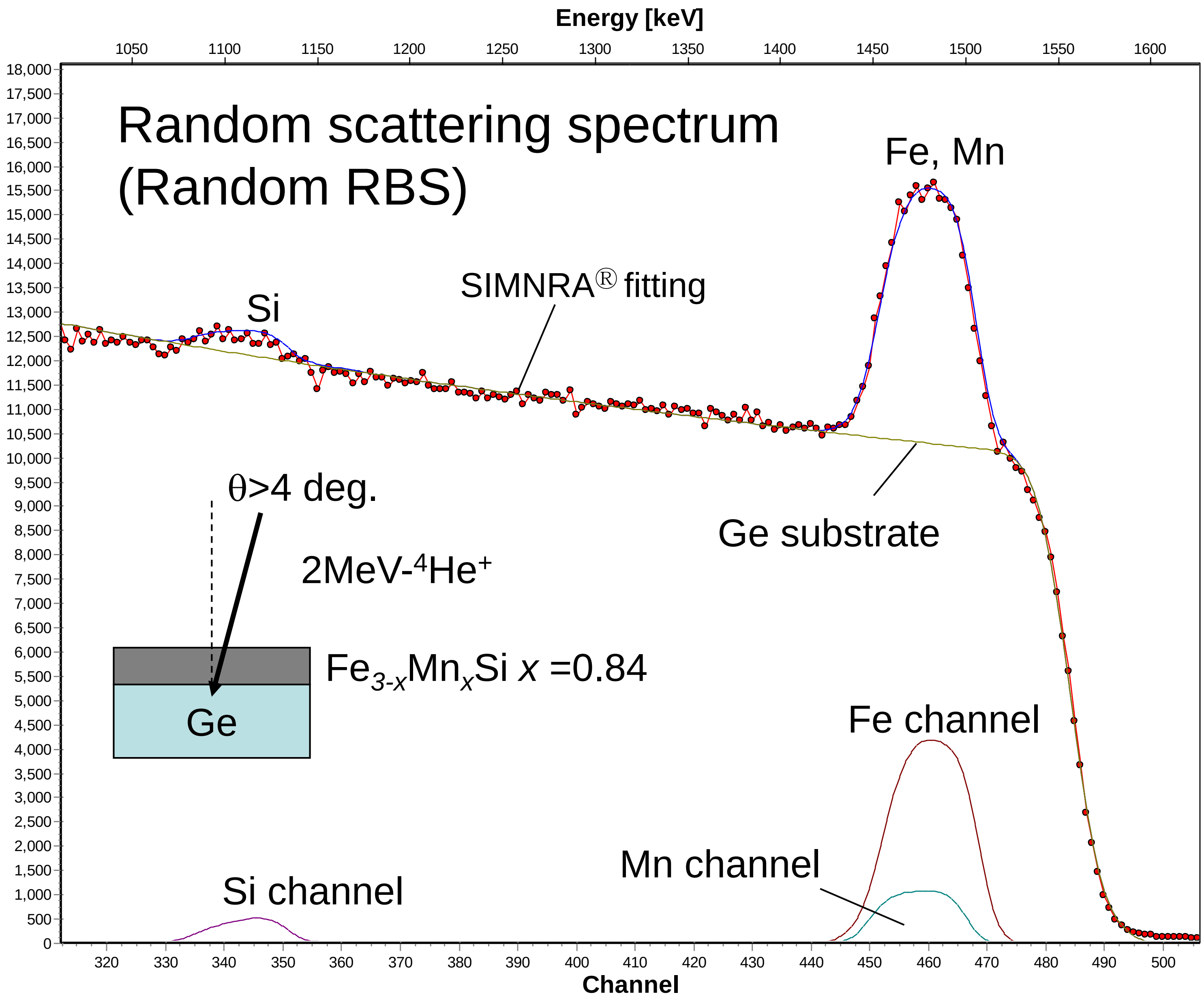
RBS measurements at JAEA-TIARA

Dual Beam Analysis Line(MD2)
ion channeling set-up at low temperature

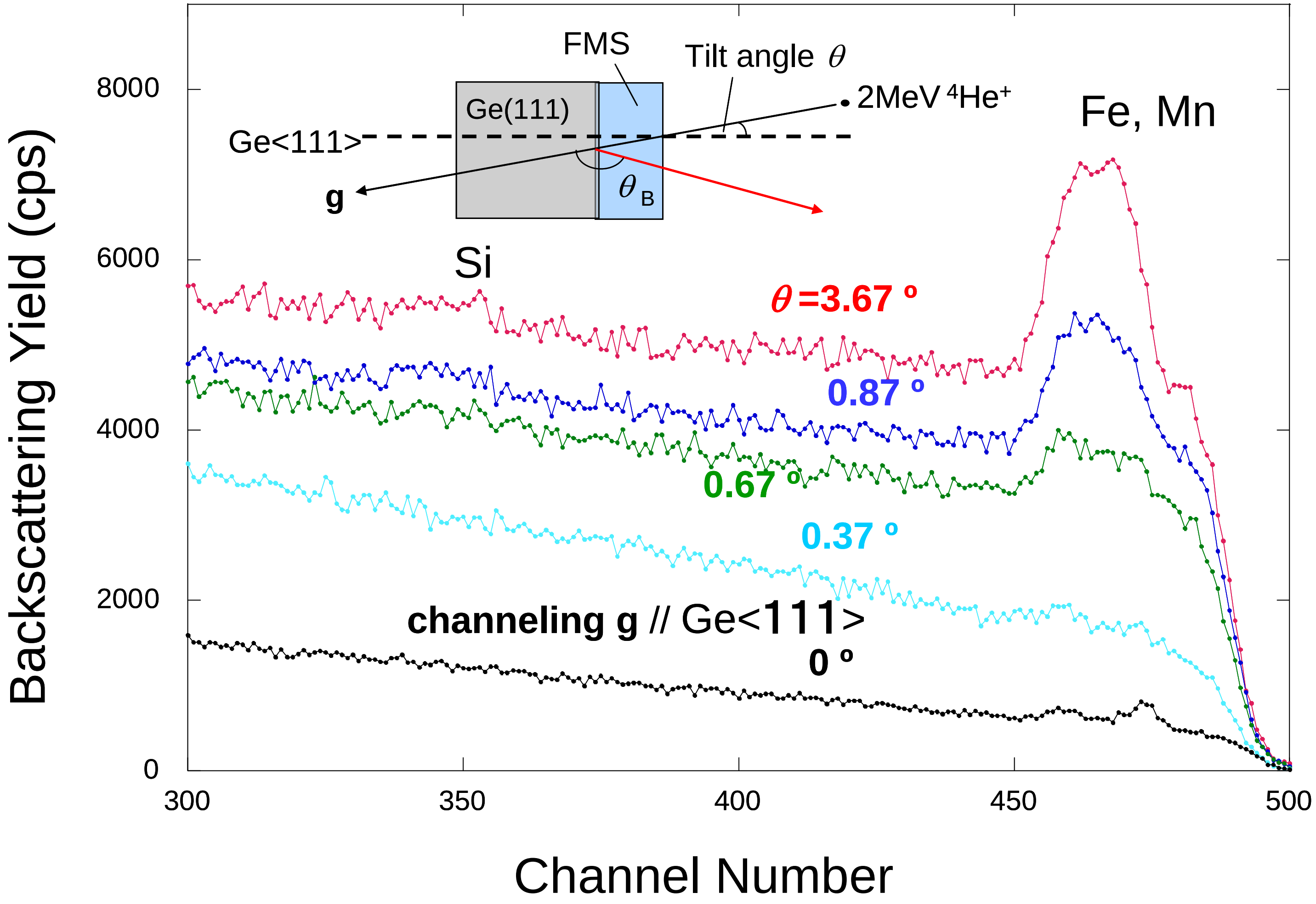


（Cited from Homepage of JAEA-TIARA)

Rutherford Backscattering (RBS)



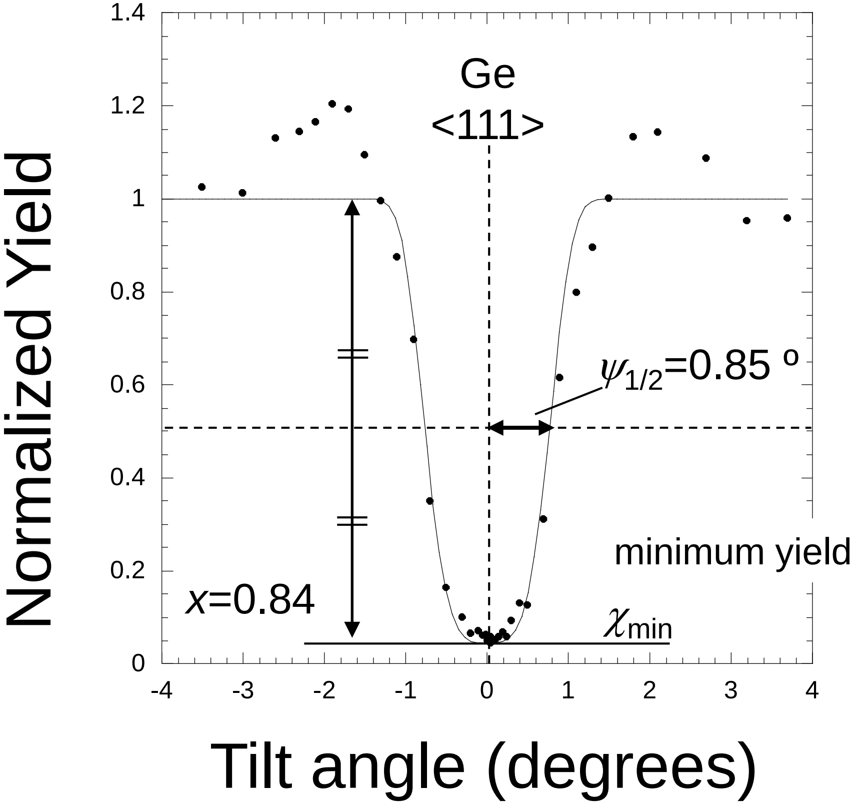
RBS measurements from aligned to random spectrum

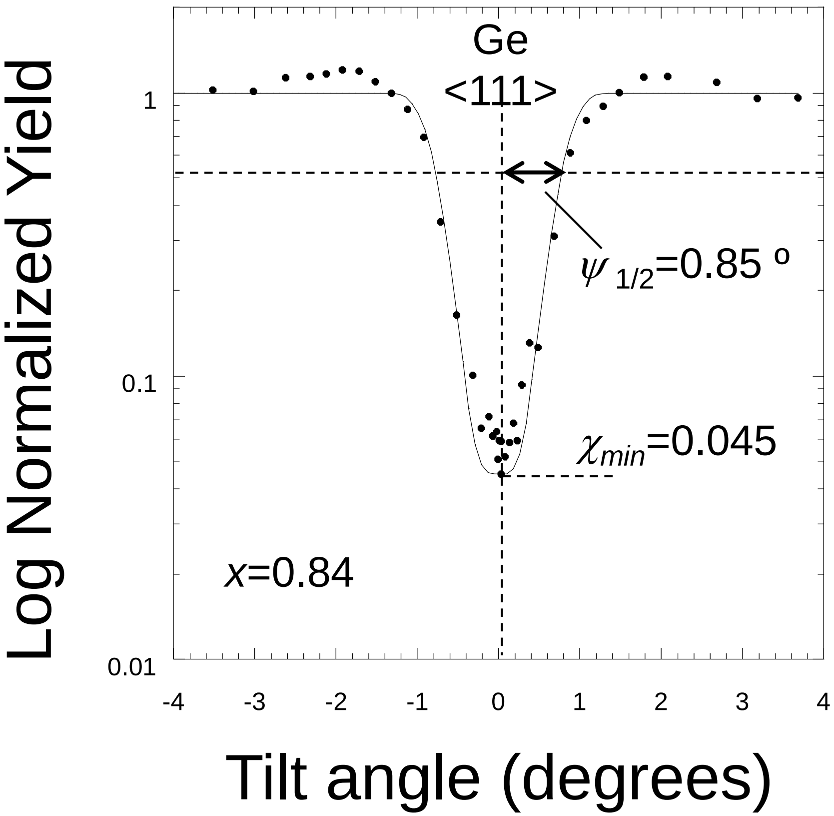


When a sample is tilted from aligned angle, RBS spectrum changes continuously from channeling to random scattering.

Angular yield profiles, Channeling parameter

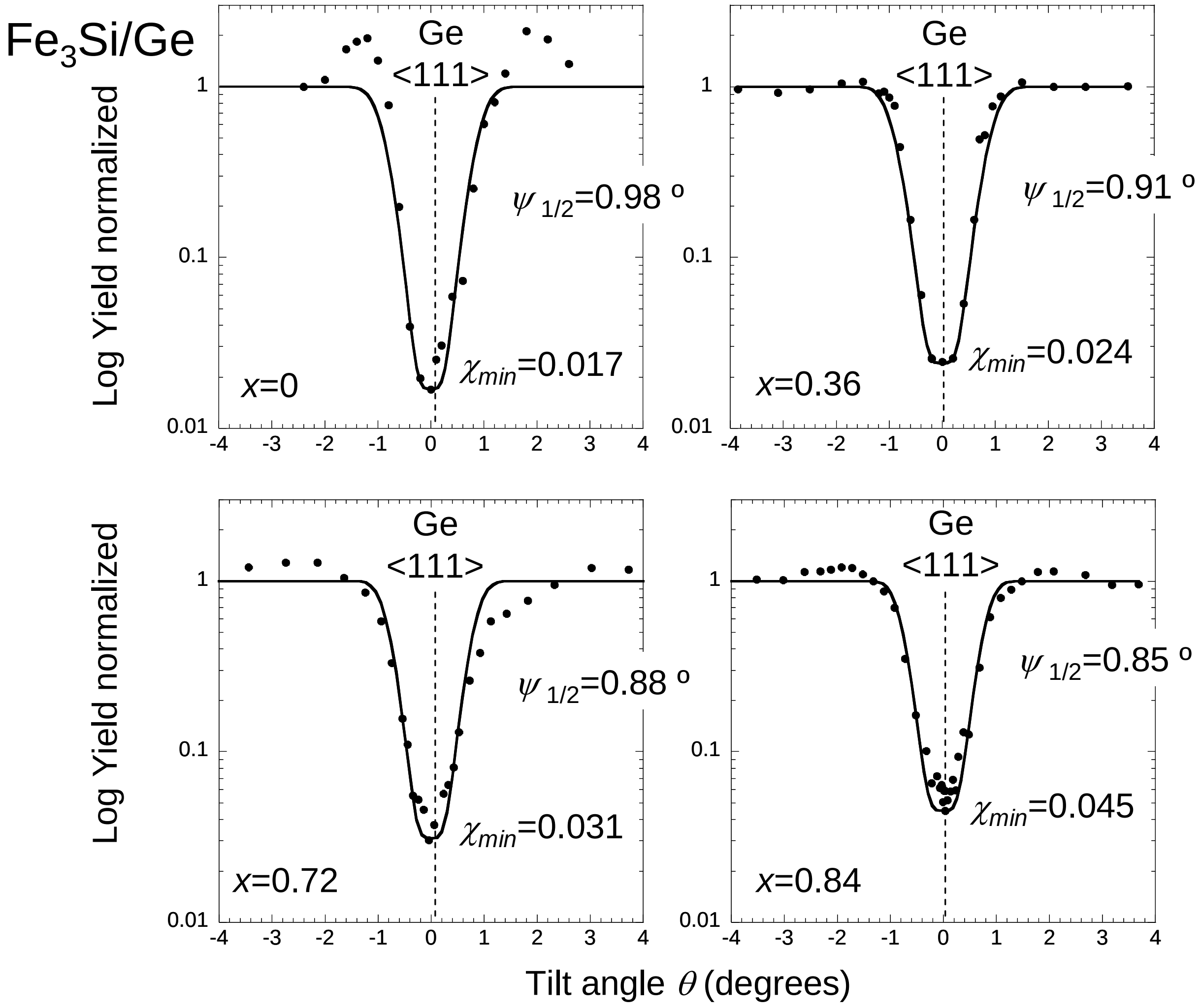
$$\chi(\theta) = 1 - \left(1 - \chi_{\min}\right)\exp\left(-\ln 2\left(\frac{\theta - \theta_0}{\psi_{1/2}}\right)^m\right)$$



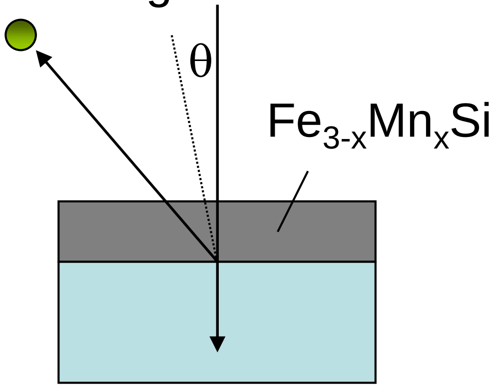


Using the upper equation, deconvolution of angular yield profile for Fe and Mn can be performed and channeling parameter $\chi_{\min}$ and $\psi_{1/2}$ were obtained.

$Fe_{3-x}Mn_xSi$/Ge(111) hybrid structure at interfaces



aligned ion beam along Ge<111>



Resolution in depth ~2nm under geometric condition employed.

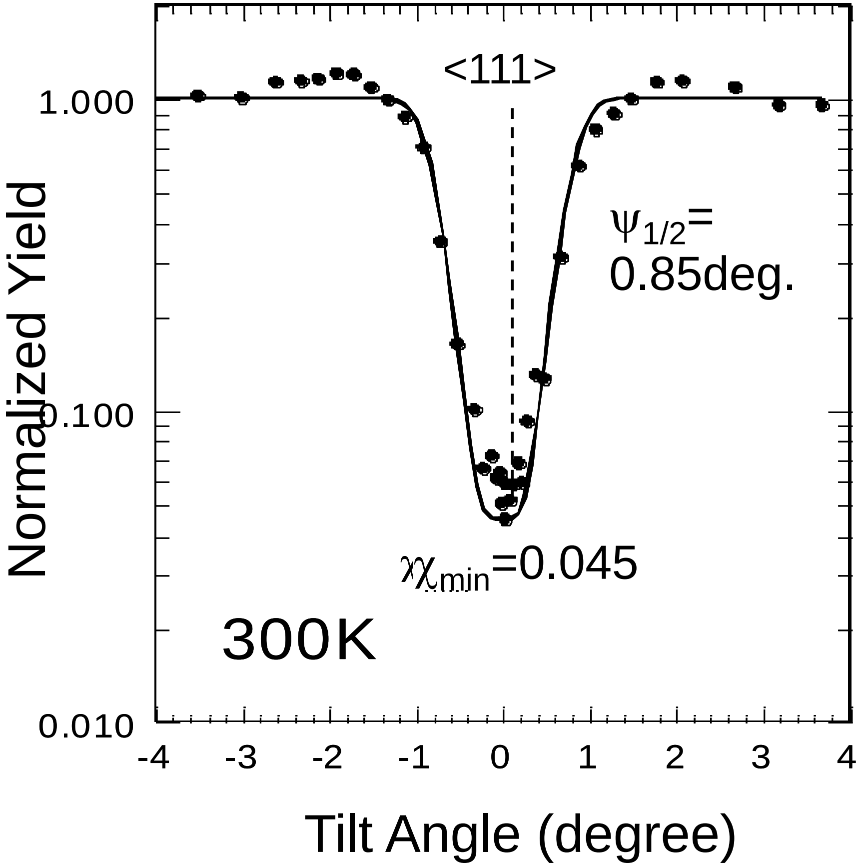
We observed systematic increase of the minimum yield and decrease of the critical half angle as Mn content increased. All FMS with each Mn content maintained epitaxy with Ge(111).

Y. Maeda et al.: MRS Proc. ***1119E*** *(2008) 1119-L05-02.*

Angular yield profiles at the interfaces with Ge(111)

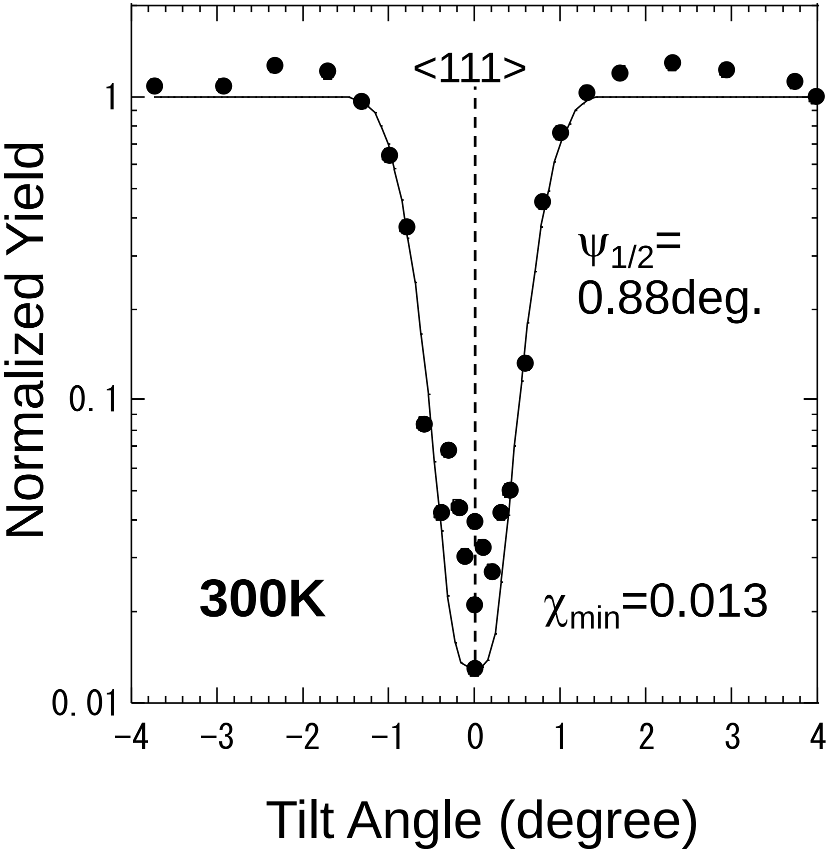
FMS/Ge

Fe_2MnSi/Ge(111)

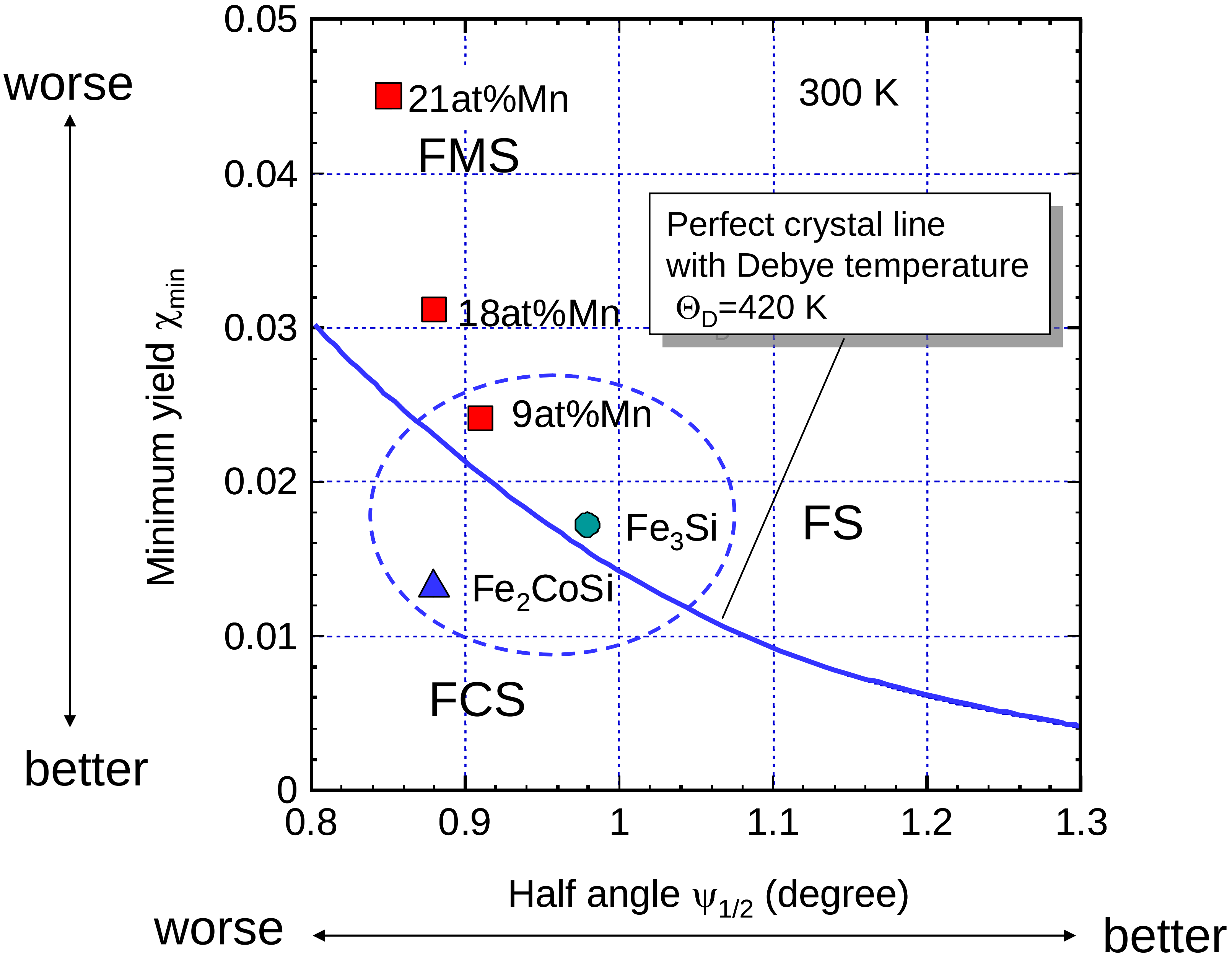


FCS/Ge

Fe_2CoSi/Ge(111)



Summary of results



Toward quantitative analysis using channeling parameter

Barrett-Gemmell model teaches us the way to quantitative analysis using channeling parameter (χ_{min}, $\psi_{1/2}$).

$$\chi_{\min} = 18.8Nd\underline{\langle u\rangle}^2\sqrt{1+\frac{1}{\zeta^2}}$$

$$\zeta = \frac{126\underline{\langle u\rangle}}{\psi_{1/2}d}$$

<u>: total atomic displacement
N: atomic density
d: interatomic spacing in axial directions

Fortunately, we can solve above simultaneous equations using elementary mathematics.

1

*J. H. Barrett, Phys. Rev. B **3** (1971) 1527.*
*D. S. Gemmell, Rev. Mod. Phys. **46** (1974) 129.*

How can we deduce <*u*> from channeling parameter?

$(\chi_{\min}, \psi_{1/2})$ deduced from angular yield profile

2

$$A = \left(\frac{\psi_{1/2}\, d}{126}\right)^2, \quad B = \left(\frac{\chi_{\min}}{18.8Nd}\right)^2$$

$$\langle u \rangle(\mathring{A}) = \frac{1}{\sqrt{2}}\sqrt{\sqrt{A^2 + 4B} - A}$$

Remarks: under the condition at the same energy of incident ions

3

Y. Maeda et al.: MRS Proc. ***1119E*** *(2008) 1119-L05-02.*

Y. Maeda et al.: Thin Solid Films ***519*** *(2011) 8461-8467.*

Total atomic displacement along atomic row

Total displacement can be written by sum of contributions of thermal vibration and static displacement due to some imperfection in the atomic row.

$$\langle u \rangle^2 = \langle u_{th} \rangle^2 + \langle u_s \rangle^2$$

For perfect crystals or crystals with small imperfection being not detectable

$$\langle u \rangle^2 = \langle u_{th} \rangle^2$$

4

Calculation of $\langle u_{th} \rangle$

Debye model teaches us the one dimensional thermal vibration of a given atom, if the Debye temperature Θ_D of material is known.

Only for *i-th* element,

$$\langle u_{th} \rangle (\mathring{A}) = 12.1 \left[\left(\frac{\phi(y)}{y} + \frac{1}{4} \right) \Big/ \mu_i \Theta_D \right]^{1/2}$$

$$\phi(y) = \frac{1}{y} \int_0^y \frac{t}{e^t - 1} dt, \qquad y = \frac{\Theta_D}{T}$$

μ_i : reduced mass

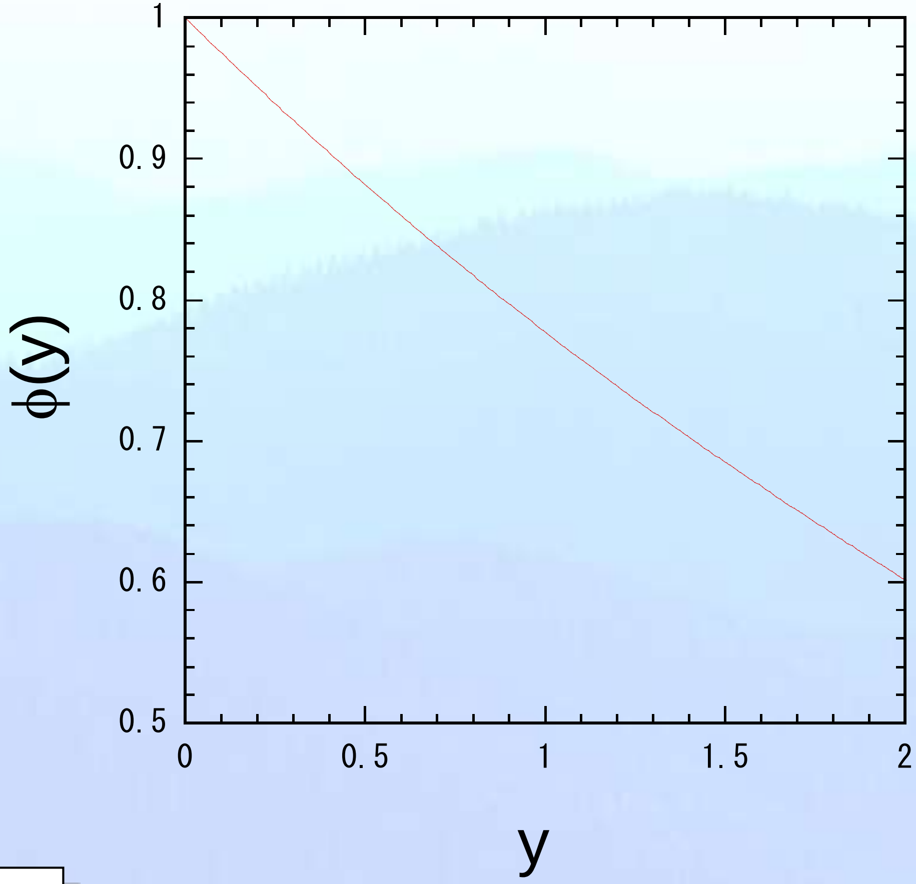
5

Wei-Kan Chu et al.,
Backscattering Spectrometry, AP

First order Debye function

$$\phi(y) = \frac{1}{y}\int_0^y \frac{t}{e^t - 1}\,dt,$$

$$y = \frac{\Theta_D}{T}$$



Case of Fe_2MnSi
Θ_D=420K
T=300K
y=1.4

6

Calculation of static displacement $\langle u_s \rangle$ due to imperfection

$$(i)\ \langle u \rangle^2 \geq \langle u_{th} \rangle^2$$

$$\langle u_s \rangle = \sqrt{\langle u \rangle^2 - \langle u_{th} \rangle^2}$$

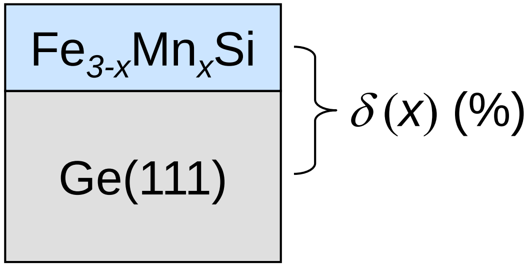
$$(ii)\ \langle u \rangle^2 \leq \langle u_{th} \rangle^2$$

$$\langle u_s \rangle = 0$$

corresponding to perfect crystals
or crystals with not detectable imperfection

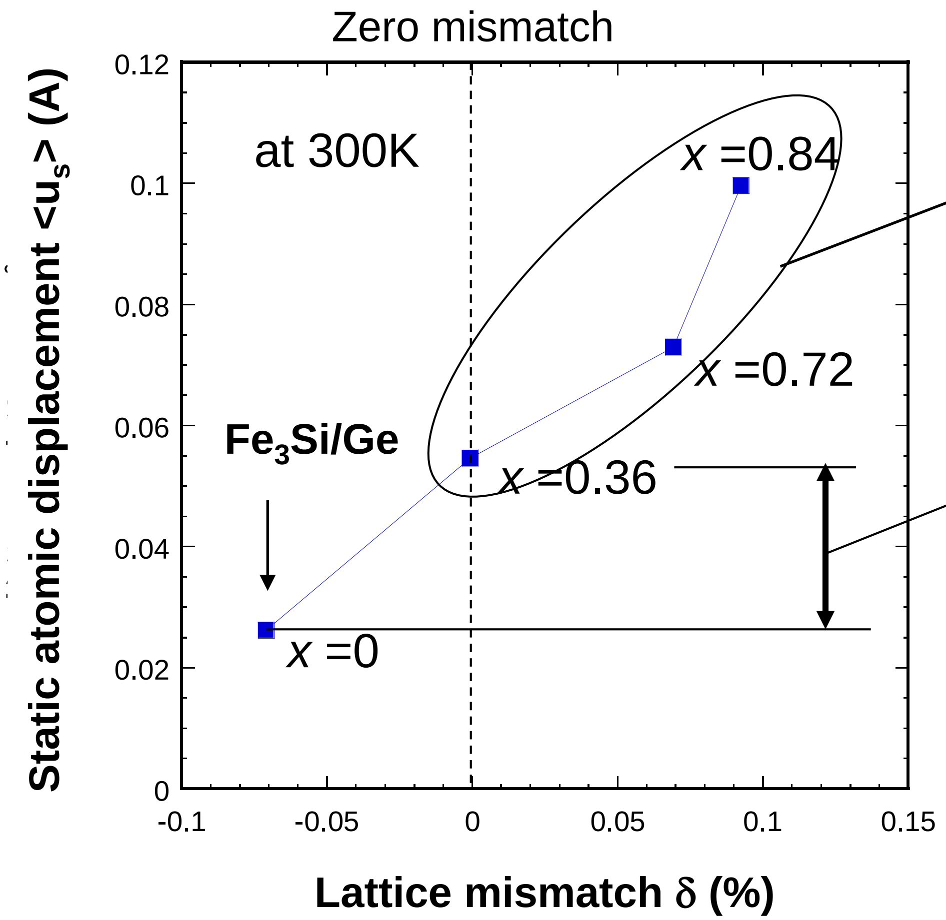
The static displacement can be obtained from subtraction between measured total displacement and calculated thermal vibration.

Static atomic displacement $<u_s>$ at interface



Lattice mismatch between FMS and Ge

$$\delta(x) = \left(\frac{(5.653+0.011x)-5.657}{5.657}\right)\times 100$$

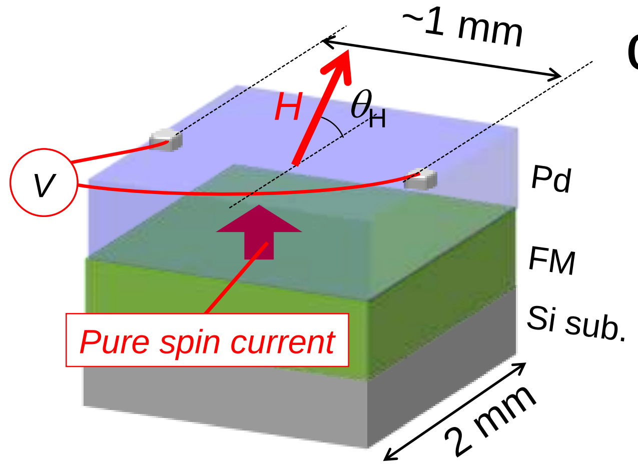


Strong correlation between $<u_s>$ and lattice mismatch δ at the interface was found. This means that imperfection may mainly be introduced by the lattice mismatch.

This difference may come from B site randomness due to Mn occupation.

Ferromagnetic resonance (FMR) measurements

(Y. Andoh, APEC-SILICIDE 2013)

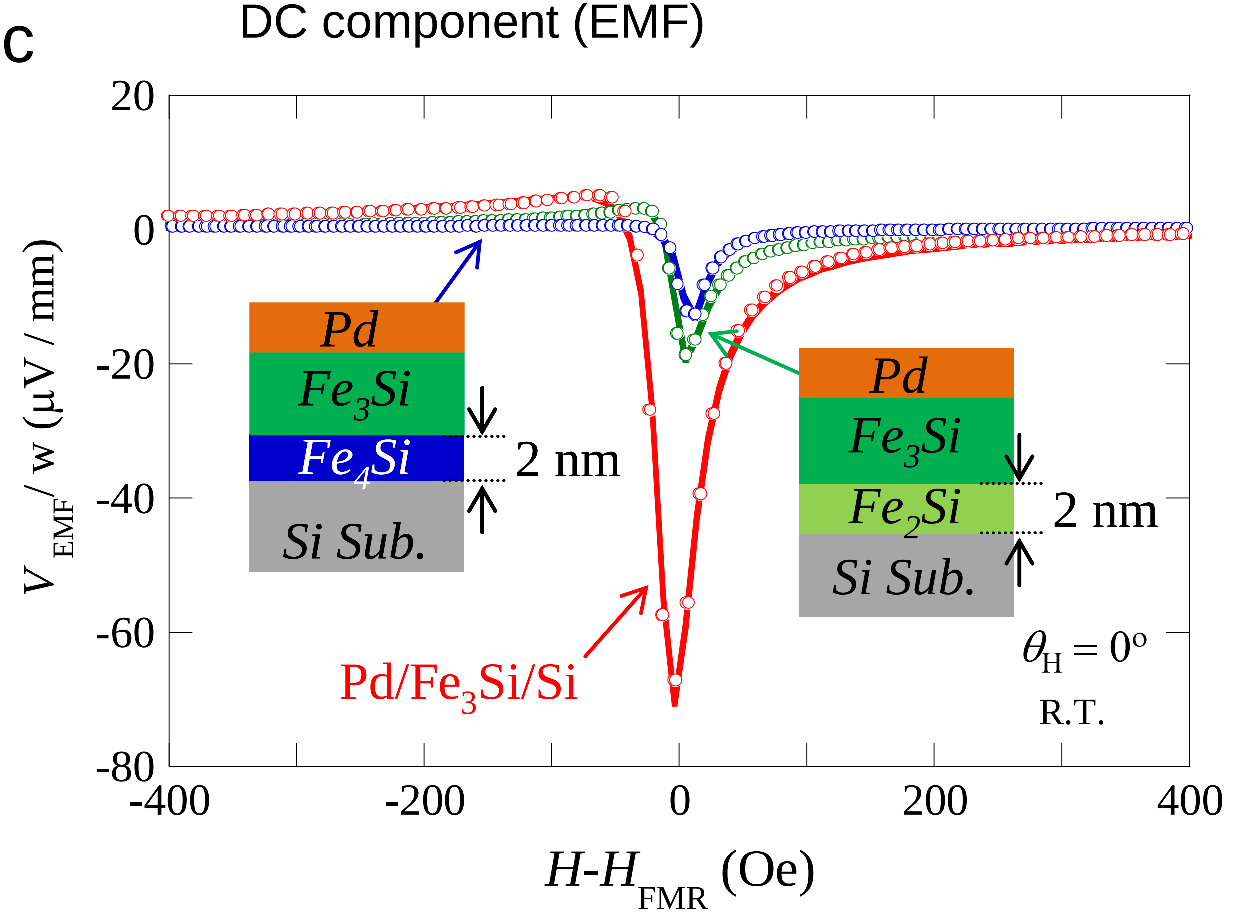


Measurements

ESR（Bruker EMX10/12）

Temp.：300 K
Microwave power：200 mW
Frequency : 9.6 GHz

DC component (EMF)



These FMR measurements give the first confirmation that crystal quality of Fe_3SI directly controls performance of spin injection.

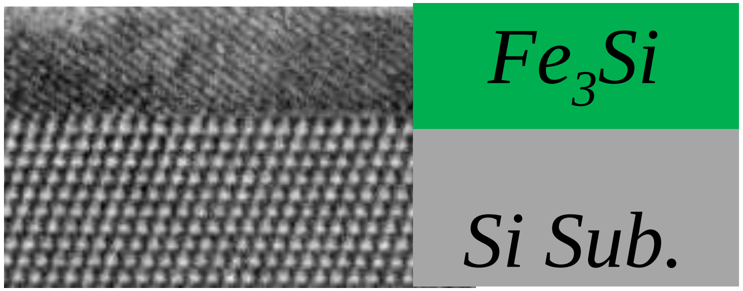
Conclusions

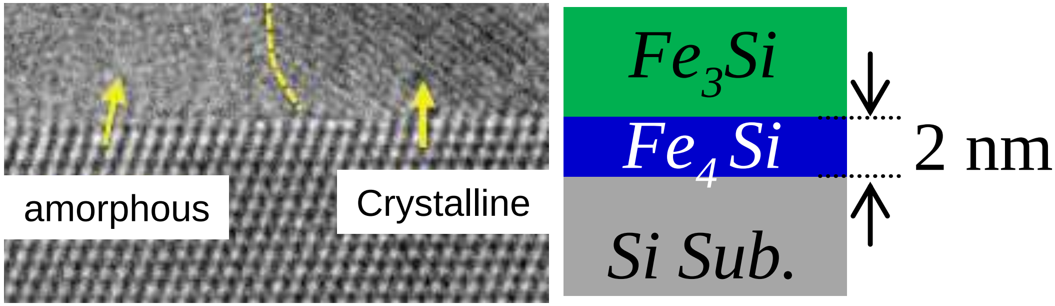
- Ion beam analysis (IBA) is helpful and powerful for analysis of epitaxial hetero-interfaces.
- It is possible to deduce quantitative and average information such as atomic displacements at a give depth or interface from the ion channeling parameter.
- Most recently, spin injection experiments are going more active. IBA data will be helpful for understanding its properties.

Thank you for your kind attention!

Ion channeling of Fe_3Si, $Fe_4Si/Si(111)$

LTMBE





Results of ion channeling and static atomic displacement and spin injection experiment

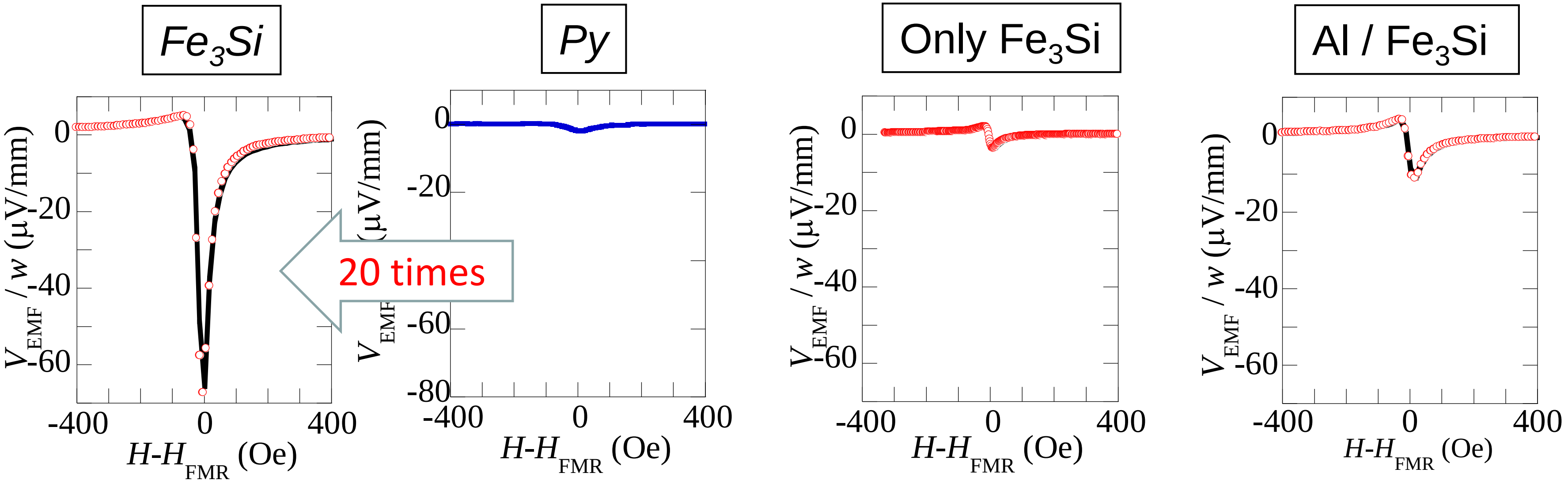
	δ(%) at IF	χ_{min}	$\psi_{1/2}$(deg.)	$<u_s>$(A)	*emf* (mV)
Fe_3Si/Si	+4.13	0.18	0.99	0.25	~68
Fe_4Si/Si	+4.15	0.23	0.95	0.52	~18
Fe_3Si/Ge	-0.05	0.02	0.98	0.09	

Dynamical spin injection into Pd layer using Fe_3Si

High quality Single crystalline Fe_3Si

① Large EMF

② Control experiments



To realize highly efficient generation of pure spin current…

✓High quality FM layer with uniform magnetic properties.

✓Small Gilbert damping constant

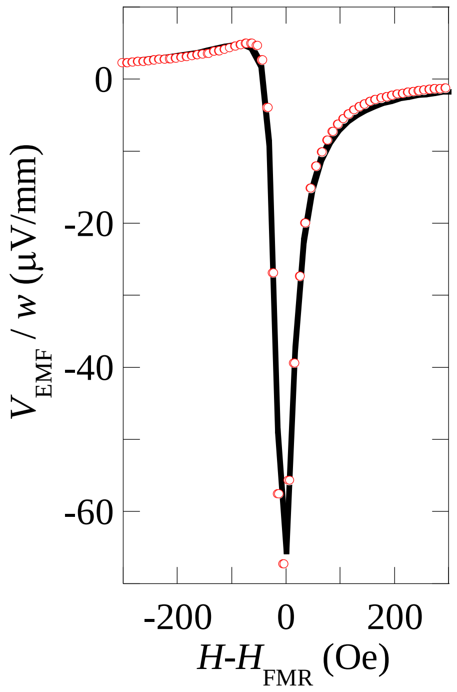
⇒ <u>Ferromagnetic silicide Fe_3Si with homogeneous quality is promising</u>.

(Y. Andoh, APEC-SILICIDE 2013)

Comparison of EMF for various FM samples

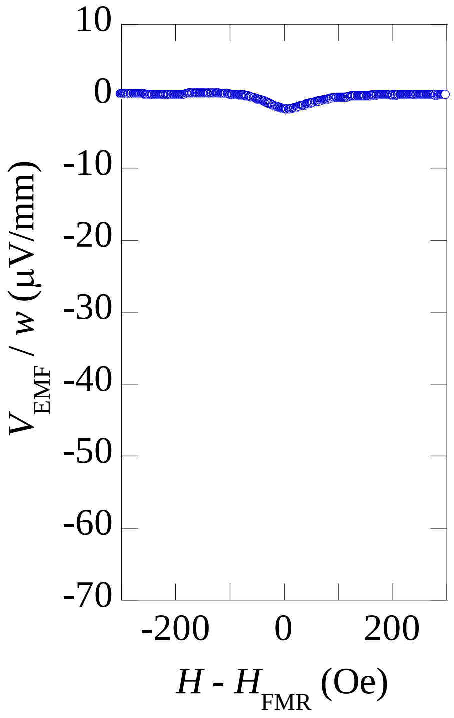
Single crystal

Pd/Fe_3Si



V_{ISHE}/w
$= 67.1\ \mu V/mm$

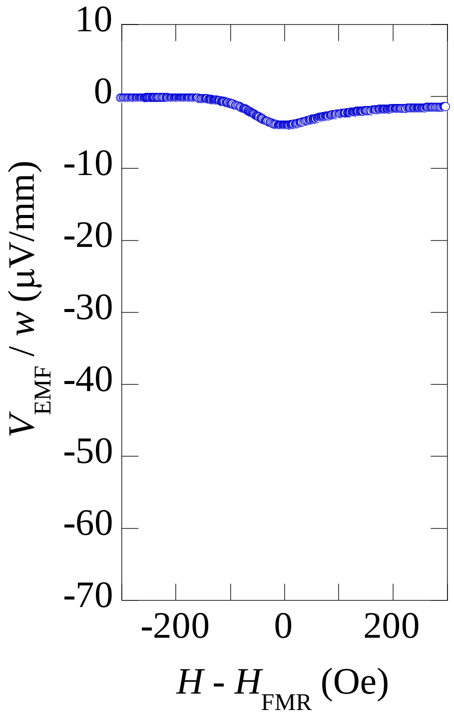
Pd/Py



V_{ISHE}/w
$= 3.05\ \mu V/mm$

Single crystal

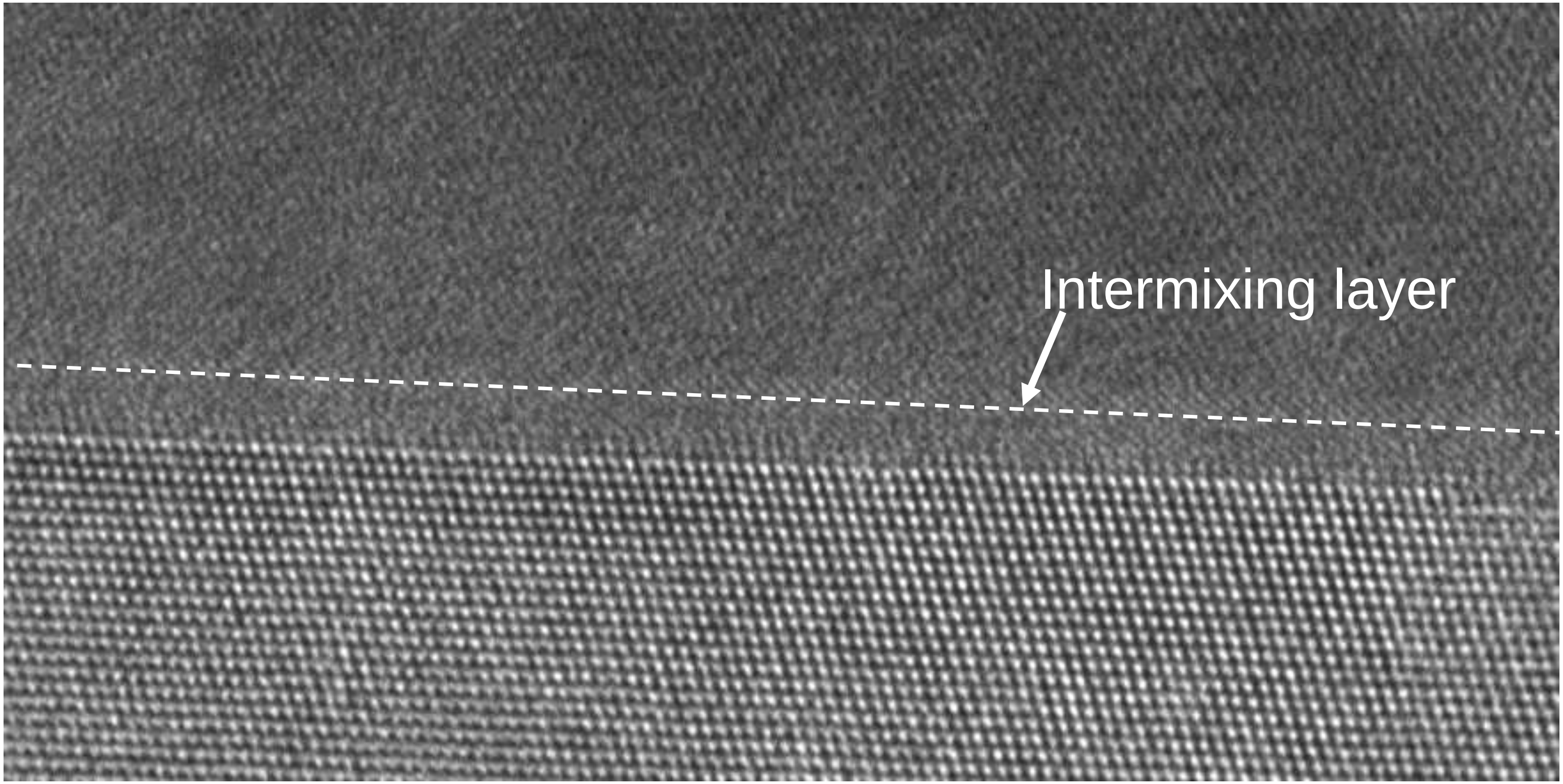
Pd/Co_6Fe_4



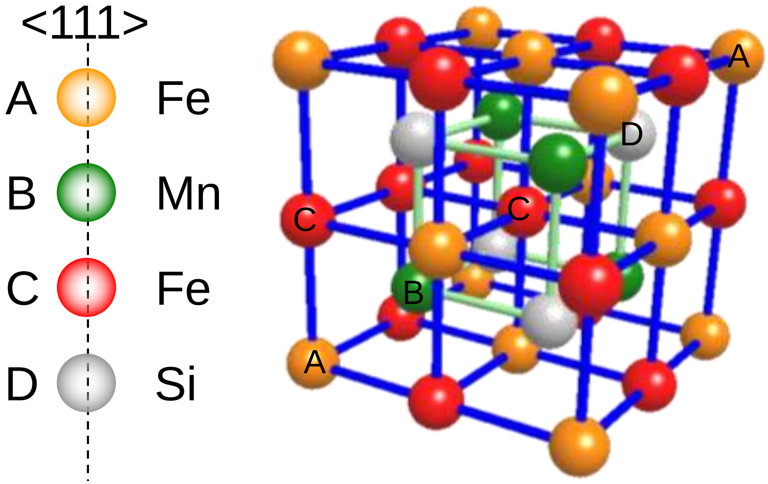
V_{ISHE}/w
$= 2.92\ \mu V/mm$

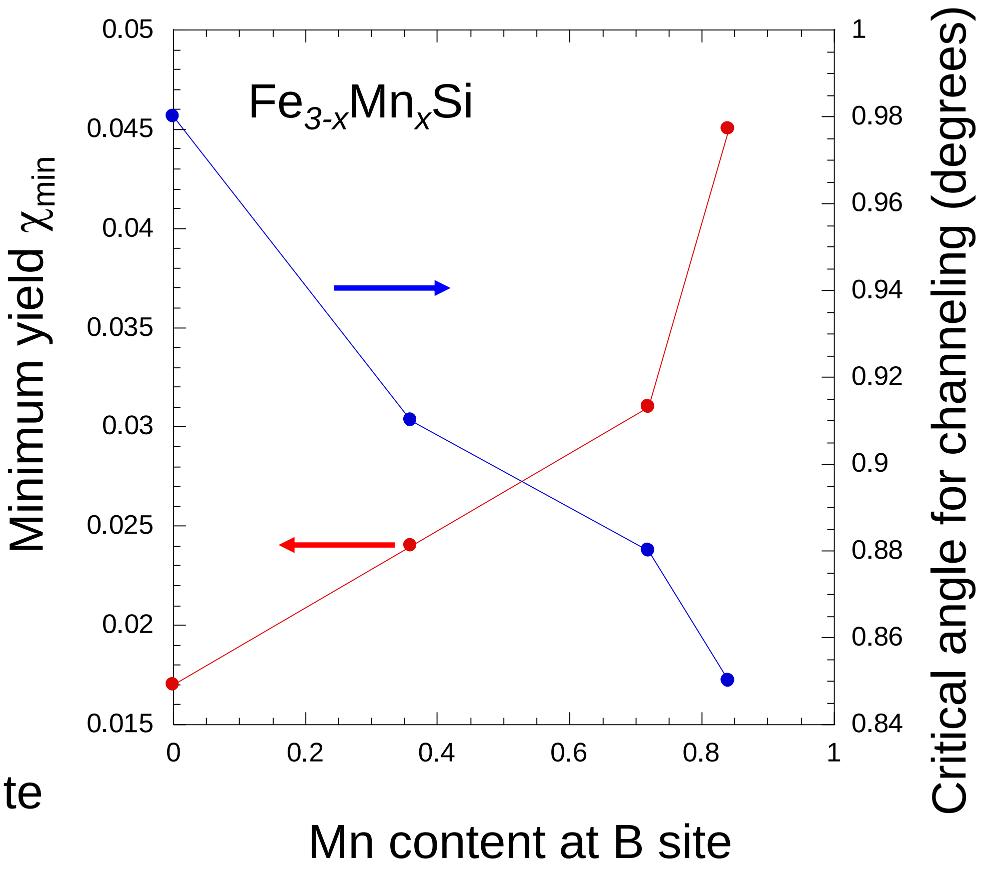
(Y. Andoh, APEC-SILICIDE 2013)

$Fe_2MnSi(111)/Ge(111)$ T_d=200°C



Axial channeling parameter (χ_{min}, $\psi_{1/2}$)





NMR and Moessbauer measurements revealed that in every Mn content, Mn atoms preferably occupy at the B site in the lattice.

We found that increase of Mn content at the B site brings randomness of the atomic row along <111> direction. This behavior has been observed as increase of a Debye-Waller factor in EXAF, XANES measurements. Randomness along <111> may be introduced by weak chemical bonds around Mn atoms at the B site.

Y. Maeda et al.: Thin Solid Films ***519*** *(2011) 8461-8467.*